

STRATEGIC ENERGY TECHNOLOGY PLAN

Scientific Assessment in support of the Materials Roadmap enabling Low Carbon Energy Technologies

Wind Energy

Authors:

L.G.J. Janssen (rapporteur), R. Lacal Arántegui, P. Brøndsted, P. Gimondo, A. Klimpel, B.B. Johansen, P. Thibaux

JRC Coordination:

R. Lacal Arántegui, E. Tzimas



EUR 25197 EN - 2012

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European Commission
Joint Research Centre
Institute for Energy and Transport

Contact information

Address: Westerduinweg 3, NL-1755 LE Petten, The Netherlands
E-mail: roberto.lacal-arantegui@ec.europa.eu
Tel.: +31 224 56 53 90
Fax: +31 224 56 56 16

<http://iet.jrc.ec.europa.eu/>
<http://www.jrc.ec.europa.eu/>

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JRC 68191

EUR 25197 EN
ISBN 978-92-79-22936-7 (pdf)
ISBN 978-92-79-22935-0 (print)
ISSN 1831-9424 (online)
ISSN 1018-5593 (print)
doi:10.2790/42568

Luxembourg: Publications Office of the European Union, 2012

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Printed in the Netherlands

Preamble

This scientific assessment serves as the basis for a materials research roadmap for wind power technology, itself an integral element of an overall "Materials Roadmap Enabling Low Carbon Technologies", a Commission Staff Working Document published in December 2011. The Materials Roadmap aims at contributing to strategic decisions on materials research funding at European and Member State levels and is aligned with the priorities of the Strategic Energy Technology Plan (SET-Plan). It is intended to serve as a guide for developing specific research and development activities in the field of materials for energy applications over the next 10 years.

This report provides an in-depth analysis of the state-of-the-art and future challenges for energy technology-related materials and the needs for research activities to support the development of wind power technology both for the 2020 and the 2050 market horizons.

It has been produced by independent and renowned European materials scientists and energy technology experts, drawn from academia, research institutes and industry, under the coordination the SET-Plan Information System (SETIS), which is managed by the Joint Research Centre (JRC) of the European Commission. The contents were presented and discussed at a dedicated hearing in which a wide pool of stakeholders participated, including representatives of the relevant technology platforms, industry associations and the Joint Programmes of the European Energy Research Associations.

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1. Technology and system state of the art and challenges

The main challenge for wind energy developments, and main objective of the technology evolution, is the reduction of cost of wind energy. This needs to be obtained through reductions in capital investment and maintenance costs and through maximising the annual energy production.

1.1 Description of reference technologies

Wind energy power generation has been growing over the last decade by 25% per year. The total worldwide installed capacity during 2010 was over 38 GW and at the end of 2010 the total installed capacity reached 199 GW [1, 39] of which 3 GW is offshore. In Europe the installed capacity at the end of 2010 is about 86 GW.

The largest wind turbines installed are growing from 2 MW in 2000 to 5 – 6 MW today with rotor diameters up to 126 m, and manufacturers are working on designs up to 10 MW with rotor diameters of 150 to 180 m.

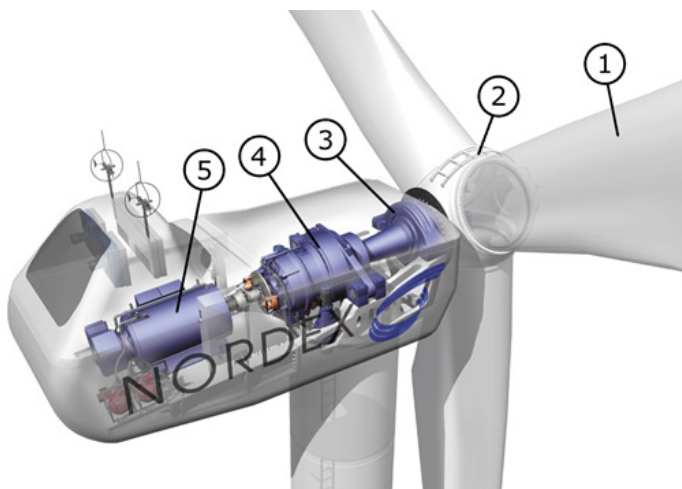


Figure 1: Turbine with Gearbox (courtesy Nordex)

Main components of wind turbines include rotor blades, rotor hub, main shaft, gearbox, generator and power converter, all hosted in a nacelle supported by a bedplate that is mounted on a tower and rotates thanks to a yaw bearing system see Figure 1.

Direct drive turbines have a gearless drive train with a low-speed generator, see Figure 2.

The materials used in the main components are:

- The blades are produced from polyester or epoxy reinforced with mainly glass fibres and to some extent carbon fibres in combination with polymer foam or balsa wood for the sandwich parts. The blades are mostly produced in two halves, the upper and lower part, and are joined using adhesive bonding. Both the aerodynamic shape as the structural parts of the blades are produced from fibre reinforced materials. The blades are bolted via a pitch bearing to the hub,
- The rotor hub, the main shaft, the gearbox, the bedplate and the tower are basically produced from different types of low-alloy steels and cast irons. Again here the functional as well as the structural shapes are combined,

Onshore installations in Europe have an average capacity factor of 25 %. Offshore wind farms, with stronger, steadier winds, may reach capacity factors in the range of 40 %. Even considering the planning constraints relating to shipping lanes, fishing, bird migration, and the like, the world has abundant space for offshore projects. But conditions during offshore installation, operation and maintenance may be harsh, and so products must be highly reliable.

Almost all commercial large turbines for both on and offshore locations are horizontal axis, 3 bladed turbines with tubular steel towers.

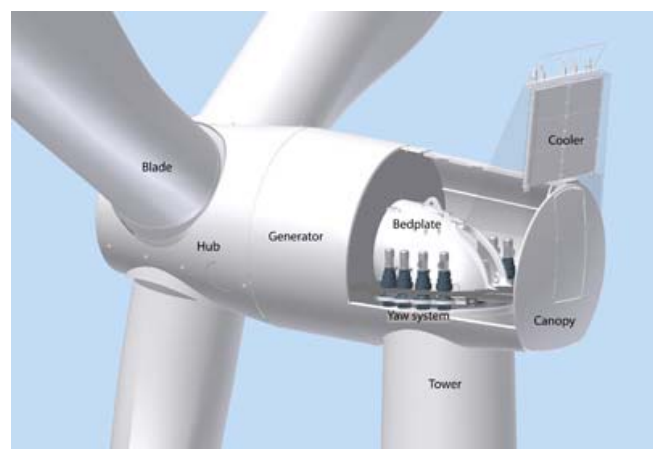


Figure 2: Direct drive turbine (courtesy Siemens)

- Electric generators are basically made of a rotor and a stator and materials used include magnetic steels and copper for windings in electromagnet generators or steels, copper, boron, neodymium and dysprosium in permanent magnet generators. High-temperature superconductor (HTS) generators, still in their development phase, use basically HTS wire and ceramics.
- The power electronics converter, whether partial or full, ensures that the output electrical signal complies with the power quality of modern grid codes, and enables the variable speed operation of the wind turbine. In addition, PE devices used in wind turbines are part of the control system and help achieving safe control and the maximum power output.

The overall challenges for the materials used in wind energy that need to be addressed through research and development are:

- Life cycle management, from ore processing until waste reuse and recycling. This needs to be done by means of environmentally-friendly production technologies. In many cases existing processes need to be adapted. New materials (nanomaterials, fibres and polymers for blades, lubricants, permanent magnets)
- Resource management: Europe being a continent with very little raw material resources should assure its strategic access to these products and or develop alternatives for the critical materials,
- New materials which make innovative solutions technically feasible,
- Materials for extreme conditions of exploitation, such as offshore and cold climate conditions

1.2 Blade design and production

Wind turbine blades must be strong enough to withstand loads from continuously-varying wind speeds. In the 20 year lifetime of a wind turbine the number of load cycles will be between 100 million and 1 billion. Next to that the blades will have to withstand extreme loads that can occur during extreme weather conditions or during abnormal events without too large deflection to prevent the blades hitting the tower. These loading conditions in combination with the required low gravitational forces lead to a selection of material that combines a relative low density with a high stiffness and fatigue resistance.

Fibre Reinforced Polymer (FRP) materials offer the designer an attractive range of solutions as materials properties and component response can be tailored to design specifications. Hence, as the wind turbine blades are complex and heavily loaded, the FRP composites in form of laminates or sandwich substructures are the overall dominant materials used for the blades. Correctly engineered these materials can fulfil requirements for very complex structures and give a variety of possibilities in order to optimize the performance of the blade. The complexity also creates demanding challenges for new research and engineering development and design [4-6].

The main challenges for the FRP composite materials are:

- To ensure a consistent quality of fibres, sizings, and resins. The performances of the composites are very dependent of consistency between fibre surface treatments (named sizings), resin quality and manufacturing parameters. Increasing demands for both fibres and resins generate and develop markets for new suppliers and requires additional quality assurance for the raw materials deliverables.
- To increase production volumes in the coming decades at the pace that they increased during the last decades. This gives a lot of pressure to the complete supply chain of blades. Not only on the supply chain of the raw materials but also on the manufacturing capacity to process these volumes.
- To ensure uniformity in the manufacturing processes and hereby maintain a product quality. This is done by close control of process parameters and by a post manufacturing quality control and inspection of the new blades.
- To develop accurate analytical material models and efficient analyses tools that can be used in blade design.

- To enable reproducible and standardized testing and ensure consistently the material properties in such a way that improved and reliable experimental material models can be generated and material safety factors can be lowered to optimize the design of rotor blades with respect to structural properties, material consumption and production time.
- To introduce new high performance fibres and resins in order to fulfil the design requirements of the future large lightweight blades. This will lower material consumption and component weight and hereby reduce the gravitational fatigue loading on the very large blades.
- To ensure recyclability used in cradle to cradle and cradle to grave concepts. Recycling of blades has not been the hot topic and most of the current blades are not considered to be recycled and reused. At present the most economical solution for disposal is landfill. Landfill disposal will not be acceptable in the future and incineration leads to hazardous by-products and scrap that needs to be disposed in landfills. The composite material is a valuable material resource and for the future composites must be reused or brought back to origin [7].

1.3 Tower design and production

The tower of a wind turbine is made of steel (97%) or of prestressed concrete (3%) [8-27]. The steel tower is made of a few sections of 20-25 m length. At the end of each section, a flange is welded in order to allow for assembly on-site with bolts. Each section is made of shells coming from rolling in 3-roll bending of plates. The plates have generally a length of around 12 to 16 x 4 m, max format of supply of steel plates, in order to achieve a diameter min 2.5 m up to 5 m for the shells and sections. This limitation comes from transport and bridges. The standard steel grade applied is S355J2. The shells within one section are generally welded by multi-wire automatic narrow gap submerged arc welding in 2 to 30 passes, depending on the thickness of the shell. The critical tower design criteria are buckling, ultimate load and fatigue and brittle cracking resistance up to – 50°C. The increasing size of turbines and their sitting in lower-wind sites lead to an increase of the diameter of the rotor and of the weight of the nacelle, and consequently also of the tower. One of the specificities of WEC is fatigue, with an estimated number of cycles on a lifespan of about 10^8 cycles.

Main challenges for the steel tower materials are characterized by low mass to strength ratios and cost reduction therefore to:

- Higher quality and better weldability of the steel and welding materials resulting in a significant weight reduction and higher fatigue life,
- Lower production costs of thick high strength steel plates and tower.

In relation to the overall purpose of using renewable energy, then tower production is the single biggest contributor of GHG in the manufacturing of onshore wind turbines

1.4 Support structure design and production

Most of today's offshore wind turbines are placed and planned to be in shallow and intermediate water with depths up to 45 m. However, the next generation of offshore wind farms will be located in deeper waters and dispersed more widely around the coastal waters; therefore for future wind parks, the development of new solutions is necessary. The challenge of wind resource exploitation deeper and further offshore involves that more wind turbines and ancillary equipment (e.g. maintenance vessels) will be specifically designed for those conditions. They will take into account issues such as foundations to seabed up to 60 metres depth, the difficulty of their inspection and maintenance and the saline environment.

The support structure of the wind turbines represents a significant proportion of offshore development costs. Most support structures installed or planned are based on monopile technology. It consists of a large diameter tube hammered in the sea bed. On the top of this tube a "transition piece" is grouted. The transition piece has the function to align the tower, to make the tower accessible and is situated in the splash zone, which is the part most exposed to corrosion. For a water-depth of 30m, the monopile could

have a length of 60 m, a diameter close to 5 m (depending on the installation barge) and a wall thickness of 60 to 80 mm. In total the weight is close to 500 t. The transition piece has often a weight close to 200 t. Main manufacturing technique is welding, particularly submerged arc welding.

As turbine size increases and the industry migrates into deeper waters, additional sub-structure designs will be required, see Figure 3, such as:

- Gravity base (a): these foundations resist the overturning loads solely by means of its own gravity. Advantages include that piling is not required and a lower corrosion exposure of the foundation. These are typically used at sites where installation of piles in the underlying seabed is difficult; it is an inexpensive solution suitable up to 40 m or more, but it requires a preparation of the seabed and transportation can result challenging for heavy turbines,
- Tripod (b): is a three-leg structure made of cylindrical steel tubes, The central steel shaft of the tripod makes the transition to the wind turbine tower. It is suitable up to 30 m or more and is adequate for heavy large-scale turbines, but complex to manufacture and heavy to transport,
- Jacket (b): is a lattice structure also adequate for heavy large-scale turbines in more than 40 m. It is expensive so far and subject to wave loading and fatigue failure.
- Floating (c): is suitable for very deep water (water depth > 60 m), but up to now is expensive, not yet proven and with unsolved stability issues and therefore to be further developed at a later stage.

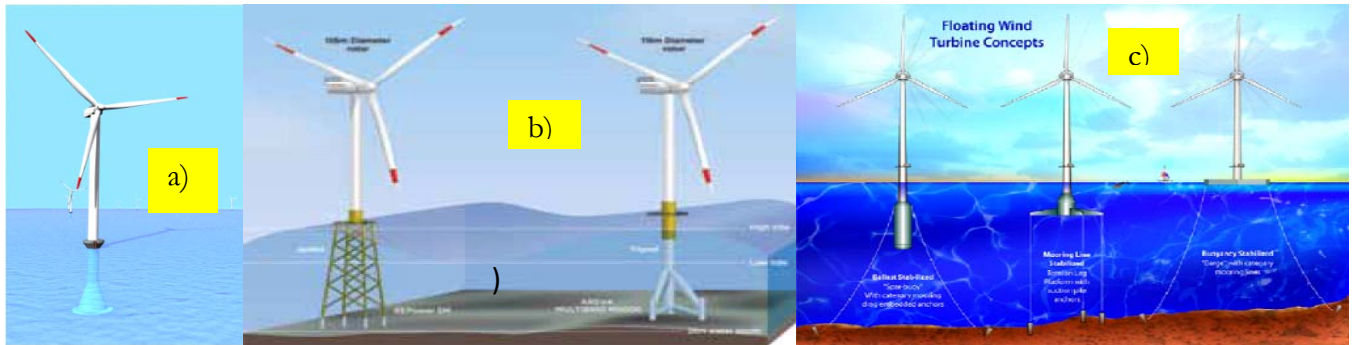


Figure 3: a) gravity base concept [30]; b) jacket and tripod substructures [28]; c) different floating wind turbine concepts [29]

At the end of 2010 monopile solutions represented the 72 % of the total offshore installations (on a per-MW basis), 20 % were gravity based and the 8 % remaining were jacket, tripod, tripods and other structures [100]. For intermediate water depth, the jacket structure, the tripod and gravity base are likely best candidates to realistically satisfy the market requirements up to 2025 and possibly over. Last but not least, it should be mentioned that there is little international guidance on the design and reliability of these structures based on various probabilities of recurrence, safety levels and design lifetime. The DNV Offshore Standard DNV OS –J101 [31] covers monopile, gravity-base and tripod structures, but makes minor explicit reference to jacket structures.

Main challenges for the support structure materials are:

- Low mass to strength ratios and cost reduction therefore to:
 - Higher quality and better weldability of the steel and welding materials, resulting in a significant weight reduction and higher fatigue life,
 - Lower production costs of high strength steel plates and tower.
- Improved (stress) corrosion resistance.
- Mass production facilities
- Achieving lower production cost of gravity base solutions through implementation of factory production techniques

1.5 Transmission system (bearings, shaft and gearbox)

The transmission system connects the rotor to the generator. It consists of a series of elements such as the main bearings, the shafts, and the gearbox. In some of the later systems designs these components tend to become integrated into one other. Additional elements by similarity are produced by the companies taking care of wind transmission such as the yaw and the pitch systems. Besides these, a wide range of winch accessories such as ropes, hooks, pulleys and blocks are used but are not herewith included.

1.5.1 Main bearings

All modern wind turbines have spherical roller bearings as main bearings. The term spherical means that the inside of the bearings outer ring is shaped like a cross section of a ball. This has the advantage of allowing the bearings inner and outer ring to be slightly slanted and out-of-track in relation to each other without damaging the bearing while running. The maximum allowable oblique angle is normally half a degree, not so large, but large enough to ensure that any possible small errors in alignment between the wind turbine shaft and the bearing housing will not give excessive edge loads, resulting in possible damage to the bearing. Most of the 500 kW and larger wind turbine models have two main bearings. Each bearing arrangement has advantages and disadvantages, and the evaluation of these properties have provided each individual type with its own setup. The main bearings are always lubricated by greasing, no matter which bearing arrangement is selected. Special grease having viscose properties even in hard frost is used. Sealing of the bearing housing is ensured by the use of a labyrinth packing. In most cases rubber sealing is not used, the labyrinth with its long and narrow passageway prevents grease from escaping.

The most common materials for bearings are martensitic or bainitic through hardened steel grade 100Cr6 and 100CrMn6 and case carburized steel grades.

Main challenges for the bearings are:

- Improved reliability and lifetime,
- Increase fatigue resistance against surface and sub-surface fatigue
- Define standardized tests to verify bearing robustness
- Define bearing specifications to guarantee robust bearing set-ups
- Understanding tribological and wear mechanisms
- New coatings and/or surface texture.
- Development of high performance biodegradable lubricants
- Development of advanced seals to reduce the friction and optimizing their functionality
- Development of on- and off-line condition monitoring for bearings

1.5.2 Main shaft

The main shaft of a wind turbine is usually a pierced shaft combined with a flange. It is made of either quenched and tempered carbon steel by means of open die forging, or it can be made of ductile iron. The surface characteristics can be drastically changed using surface treatments and coatings.

Main challenges for the main shaft are low mass to strength ratios and cost reduction therefore to:

- Improve metallurgy knowledge.
- Improve forge process and or joining process.
- Increase alloy design activities.
- Increase wear resistance of main shaft working surfaces by laser heat treatment re-melting and alloying.

1.5.3 Gearbox

In wind turbines using gearboxes this is placed between the main shaft and the generator, its task is to increase the slow variable rotational speed of the rotor blades to the higher speeds, e.g. around 1500 RPM, that are convenient for generators. High quality planetary gearboxes have become a standard for the large wind turbines due to many factors and, in fact, as gearbox sizes increase more and more double planetary designs are being developed. A planetary drive is extremely efficient to deliver high reduction ratios in a

limited space, and to transmit several times the torque of similarly sized, conventional gear units; to be compact and lightweight, and require little installation space. High levels of reliability are a feature of the planetary design thanks to the heat treatment and the distribution of stress among several load-bearing components. The standard materials choice for gears is case-carburised steel 18CrNiMo7-6. Contributing factors for the materials' performance are: steel quality (composition, hardenability, non-metallic inclusions, forging flaws) and processing technique (case carburising, grinding temper). Equally important is the dimensioning of the gears and the accuracy of the manufacturing process.

The structural components such as torque arms and planet carriers are made of ductile iron. Housings are made of highly damping grey iron or the tougher alternative, ductile iron. The solidification time of several hours due to large wall thickness of castings make the castings susceptible to casting defects such as chunky graphite and dross.

The main challenges for the gearbox are:

- Improved bearing reliability
- Integrated concepts
- Weight reduction
- Scaling up casting technology and design rules
- Non-linear and elasto-plastic finite element algorithms
- Reliable fatigue and fracture toughness models
- Tribology of poorly lubricated systems (splines, shrink fit, ...)
- Tribology of well lubricated systems (gear contact, bearings, ...)
- New coatings and gear surface finishes
- Reliable gear calculation

1.6 Nacelle bedplate and rotor hub

The nacelle bedplate is the foundation for the drive train of the wind turbine. The rotor hub is the structure that provides the coupling of the blades, via the pitch bearings, to the main shaft.

The bedplate and the rotor hub are made of low alloy steels, high strength aluminium alloys or ductile cast irons [8-27]. The production processes used are continuous casting, controlled rolling, forging and welding. The reliability of these components delivers in modern wind turbine no real problems. The deflection of the bedplate however can cause misalignment of the drive train components leading to reduction in the lifetime of bearings and the gearbox. Deflection of the rotor hub can cause serious problems for the pitch bearings and the pitch mechanism.

The main challenges for the nacelle bedplate are:

- To provide higher strength and higher rigidity structure of nacelle by application of higher strength steel plates or forgings, higher strength and higher quality cast steels or ductile cast irons or high strength aluminium alloys plates or forgings,
- Improve welding technologies of high strength steel thick plates and high strength cast steels and ductile cast iron heavy walled structures and high strength aluminium alloys thick plates or heavy walled casts.

The main challenges for the rotor hub casts or forgings to provide low mass to strength ratios and cost reduction are:

- Higher strength and higher rigidity structure by improving casting or forging procedure of high strength steels and casting of ductile cast irons,
- Lower production cost of heavy walled cast or forged steels and ductile cast iron structures,
- Improve welding technologies of high strength cast or forged steels and ductile cast iron structures and application of modern welding materials,
- Improving weldability of HSS steels castings, forgings and ductile cast irons.

1.7 Electricity generator

Electric generators they are basically made of a rotating part (rotor) and a fix part (stator). The rotating magnetic field induces electric energy in the windings in the stator. Their magnetic field can be provided by either electromagnets, which need electrical excitation applied to their copper windings, or permanent magnets (PM) which do not [32].

Which generator is used in turbines depends on the whole drive-train design: gearbox-generator-power electronics. A drive-train configuration with a 3-stage gearbox has evolved from using squirrel-cage induction generators (SCIG) into using doubly-fed induction generators (DFIG) with a partial power electronics (PE) converter. 64% of installed capacity in 2009, up from 34 % in 2000 [2], used this DFIG configuration which requires the generator to rotate at high-speed [2]. This configuration adapts well to most grid code requirements; it is proven and cost-effective and therefore preferred by investors and financing bodies for onshore wind farms. When there is no gearbox or there is but it has less than 3 stages the generator can be permanent magnet- or electromagnet-based, but it will always use a full PE converter (21 % of the 2009 installed power [2]). A 2-MW electromagnet generator is made of approximately 66 % magnetic steel, 30 % copper, and 3 % silica [33].

An alternative to the 3-stage-gearbox, DFIG is the multi-pole direct-drive (DD) generator which obviates the gearbox -a component whose failures cause significant downtime and repair costs. Electromagnet generators constituted more than 85 % of DD generators installed up to 2009, but only 54 % of those installed in 2009 worldwide [100]. Electromagnet generators are less efficient below their rated power than PM generators, and turbines naturally generate below rated power for most of the time.

New generators using permanent magnets (PMG) in the rotor achieve higher magnetic density: a 15-mm thick segment of permanent magnets can generate the same magnetic field as a 100-150-mm section of copper windings [32]. PM is an intrinsically more robust technology that has lower maintenance needs. PMGs are the choice for the majority of new wind turbine designs and therefore they will be increasingly present in future offshore wind farms as well as onshore installations. Main materials in PMGs include magnetic steel, boron, rare earth elements (REE), insulation and copper. The generator size is approximately one quarter less than its electromagnet counterpart [106] and therefore its specific mass, depends on whether it is low-speed (which matches a DD configuration), medium-speed (coupled with a 1- or 2-stage gearbox), or high-speed (coupled with a traditional 3-stage gearbox). The magnet content of a 3-MW generator is around 650 kg/MW in the low-speed case, around 160 kg/MW for medium-speed, and around 80 kg/MW for high-speed PMGs [34, 35].

The most popular permanent magnets (NdFeB) are manufactured from neodymium (Nd), iron (Fe) and boron (B), with a low but vital part of dysprosium (Dy). Praseodymium (Pr) may eventually replace up to 1 in 4 Nd, but with a certain loss in quality. Traces of terbium (Tb) can be used to prevent the PM from losing magnetic properties at high temperatures, although this is a function most commonly played by Dy. Bonded magnets are not used in the wind sector; it is the sintering process that produces the higher performance magnets required for larger wind turbine applications [122]. Nd, Pr, Dy, and Tb are REE subject to a difficult supply/demand balance (see section 2). Manufacturers employ proprietary variations of elements within the magnets to produce the desired properties and proprietary process technologies for forming magnetic shapes.

First-of-a-kind high-temperature superconductor (HTS) generators have been built in other sectors (e.g. ship propulsion) and are seen as the next technology for power generation in conventional plant and then for the wind sector. In an HTS generator a superconducting rotor allows very high field strengths to be created in the air gap of the machine, making power density extremely high. Introducing the HTS technology removes an additional 50 % of the mass of the generator, making even greater capital cost reductions possible [34]. An HTS generator is claimed to offer another advantage over the PMG, namely that the peak power consumed by the cryogenics of a DD-HTS generator is a small fraction of the normal losses in a conventional rotor, and significantly lower than the heating effects on magnets [34]. This would give the HTS rotor the highest possible efficiency and additional earnings over the lifetime of the machine. Superconducting wire costs, a key component of HTS, are reducing at a rate of around 10% per annum, and the rate of saving is accelerating as more wire becomes available.

The first HTS generator in the renewable energy sector will be delivered by Converteam for a run-of-river scheme at Hirschaid in Germany [36]. The company states that a reduced size DD-HTSG design for the wind sector will be demonstrated and trialled in 2011 and 2012, followed by a fully rated project from 2013. The first use of this technology in volume serial production is likely to be determined by the relative availability and cost of permanent magnets and HTS wire [34].

The market evolution from DFIG towards DD-PMG will bring about an increase in the use of copper, due to the higher size of the generator: a 3-MW DFIG has approximately 800 kg of copper per MW [26, 33, 123] which can be compared with 2.1 t/MW [124] in the case of a 3.3-MW DD-PMG (weight 70 t of which 10 % is copper). Therefore the move towards DD-PMG wind turbines will result in a more than doubling of the copper demand for the corresponding moved market share [35, 100]. Significant as it is, this change will not make copper a critical material for wind turbine generators but the environmental aspects of ever-lower-grade copper production could become critical in the future.

Nowadays the large majority of generators supply low voltage (LV, less than 1000 V) whereas new WT in the several-MW range are increasingly being designed for medium voltage (MV) generation of 3.3 kV or above.

1.8 Power electronics converter

Power converters are power electronics (PE) devices composed of semiconductor elements including diodes, thyristors, and controllable switches such as the popular insulated-gate bipolar transistor (IGBT). They are used to make current-source converters (CSC) and voltage-source converters (VSC). VSC technology offers faster control over a wider range of voltages and its size is smaller than thyristor controlled ones. On the other hand, VSC technology is composed of self-commutated semiconductor switches which are more expensive, have higher losses and smaller voltage ratings when compared to thyristors [107]. IGBTs are the semiconductors most commonly used in power converters.

2. Material supply status and challenges

2.1 Deployment rate

From the scenarios of SET-Plan, EWEA [37] and IEA [38] scenarios for Europe and the world were evaluated for the period 2010 to 2020/2030 and 2030 to 2050. These scenarios lead to a maximum deployment rate of about 50 GW per year over the periods considered. This maximum comes from the IEA-BLUE scenario in the period 2030 to 2050.

However the deployment rate in 2010 was over 39 GW already and BTM-Consult [39] predicts much higher deployment rates, up to 140 GW by 2020. Therefore it is decided to use as a reference for this Wind Energy Materials Report a total deployment rate 100 GW, of which about 10% will be installed offshore.

2.2 Blade materials

Wiley [40] estimated blade mass as a function of turbine capacity as shown in Figure 4. Based in these data every GW of installed power requires approximately 10 000 t of blade mass. Assuming the installation rate of 100 GW per year, the total blade mass reaches 1 000 000 t. Another approach to estimate this total blade mass based on the following assumptions: 20 000 turbines of 5 MW, each turbine has 3 blades and the weight of such blades with the current design and materials is about 18 t [41] leading to a total weight of the blade material of $(20\,000 * 3 * 18 =) 1\,080\,000$ t.

Based on these estimates the future requirements for blade material can be estimated based on a typical mass breakdown for a standard blade. This breakdown summarises as follows: 55-60% glass fibre, 30% resin, 5% glue paste en 5% other materials like gel coat, balsa wood, etc, see Figure 4.

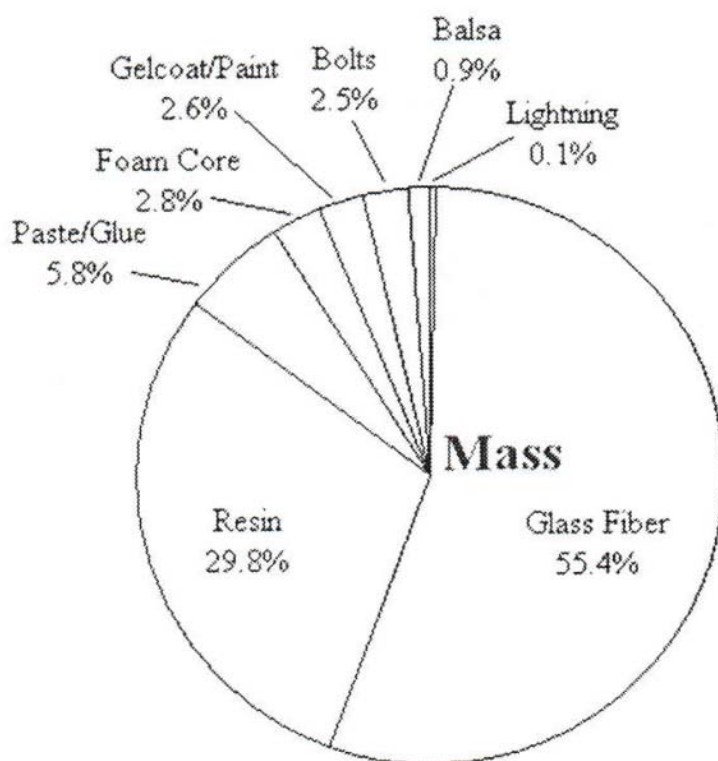


Figure 4: Blade mass break down for a standard GFRP blade [40]

report it is concluded that the global glass fibre market will grow the coming years with average growth rate of over 6 % per year.

In summary a production rate of 100 GW per year will require a supply of 600 000 t of glass fibre per year, 300 000 t of resin (polyester, vinylester, epoxy). In addition there will be respective demands for paste adhesives, foam and balsa core materials, paint etc.

Figures for production of glass fibre reinforced production in Europe show an overall production volume of approximately 1 200 000 t in 2007 [42, 43]. With an average of 50 wt% glass fibres this leads to a consumption of 600 000 t glass fibre per year in 2007.

It is expected that the global production of glass fibre composite is around 4 000 000 t.

Presently there is no shortage of glass fibre supply. Lucintel, a leading global management consulting and market research firm, has analysed the global glass fibre industry and has now published a comprehensive research report [44]. In this

Although the contribution to the total blade weight of the core materials is limited, due to the very low density (10-50 times less than glass fibre), their demand in volume is quite high. Polymers and foam core materials are mineral oil based products, and increasing oil prices will obviously affect the market. On top of that the market is dominated by only a few companies, which hinders the competition between the suppliers.

Balsa wood is also frequently used as core material. Main markets are in South America (e.g. Ecuador) and the environmental sustainability in this product is alarming and lead times can be very lengthy. Requirement and guarantees should be set for sustainable production.

2.3 Tower materials

Steel supply should not be difficult in the mid-term future. There will be a competition to secure supply between a limited number of countries producing iron ore and an increasing demand. Price of ores is expected to rise, increasing steel price, hence the competition of steel with other materials. Through the electrical arc furnace route, it is possible to recycle steel with only marginal degradation of the properties. It is then possible to use scrap instead of iron ores for the production of steel, but it is unlikely that the electrical arc furnace route will have a cost advantage compared to the blast furnace route, solely because the market forces driving the price of iron ores upwards will drive the price of scrap in the same direction.

One of the key factors in the significant improvement of the support structures will be the technological integration of the different actors in the supply chain. For onshore towers, the supply chain consists of an engineering company designing the tower, passing order to a tower manufacturer to build the tower who in turn transmits the material specifications to the steelmaker. The specific knowledge of the engineering office is in defining loads, the manufacturer controls the processing of materials and the steelmaker possesses the knowledge about the material itself. Compared to the steelmaker and the wind turbine designer, the tower manufacturer is a much smaller company. To decrease transport costs, the manufacturer is generally located in a radius of a few hundreds of kilometres from the installation site of the wind energy converter. The steelmaker delivers generally material on a larger scale, but is linked to its ability to deliver the manufacturer with an adequate service (quality, on time delivery). Delivery of steel is performed directly from the mill, or through a steel service centre, eventually also performing the cutting operations.

For offshore support structures, the supply chain is organized similarly to the supply chain for the tower. The main difference is that generally another engineering office is in charge of the design of the support structure. The wind turbine designer provides to the engineering office designing the support structure the loads at the top of the foundation. A very important issue here is the corrosion protection of the steel components.

Concrete offshore gravity bases rely on aggregate supplies and cement. Aggregate may either be extracted on land (ports) or dredged from marine reserves. Either way the reserves available are local to construction sites and extensive compared with other materials. The raw materials for cement production are also common and cement is produced across the EU. Offshore gravity bases can be re-used many times or removed and re-cycled if necessary.

2.4 Transmission system materials

There are quite few specialised wind transmission companies producing wind components worldwide. Those companies will provide to the wind industry dedicated designs based on the customer specifications, their own expertise and internal research activities. The supply chain may be more or less integrated and is quite short. The sub-suppliers of gears or castings produce raw or finished components according customer specific specifications. No technical information is generally disclosed either on products developments or about research carried out.

The current performance of wind transmission components cannot be considered completely satisfying the needs of the wind market, in terms of quality and quantity, and the more demanding needs of larger offshore turbines having to stand higher wind speeds will not reduce the pressure on performance.

In previous years there was a shortage of classical 1-2MW gearboxes and bearings, but both European and American wind transmission companies have installed new capacity in their home market and in Asia. The more demanding needs of higher towers and larger offshore turbines having to stand higher wind speeds has shifted the capacity shortage to the multi-megawatt gearboxes. Only a number of specialised suppliers are able to produce key parts for higher capacity wind turbines.

In addition, other industries use similar components for their equipment and machinery. For raw materials, notably steel, copper and carbon, the price is a critical factor in some of the wind turbine parts. Steel is used in towers, gearboxes and rotors; copper used in generators and carbon in rotor blades. Any price volatility can result in bottlenecks in the supply chain [45].

2.5 Casting and Forgings (bedplates and rotor hubs)

An important consequence of loading of wind turbines is that most components in a wind turbine are experiencing highly dynamic loads resulting in wear or fatigue of the components. This can lead to premature failure of single components or even more severe breakdowns of larger parts of the wind turbine. Many of the reasons for these problems originate from how the components were originally manufactured. Typical manufacturing processes include casting of the rotor hub, housings and frames and main shaft, see Figure 5.

About 50-60% of the structural parts in the nacelle is made of ductile iron. The commonly used grade is EN 1563/ EN –GJS-400-18U-LT. This material is cheap, easy to produce, durable, good in low temperature and has high fatigue properties. However the manufacturing technology for large-size castings needs modernisation as the shortcomings of the technology's ability to reach the wanted design is leading to unnecessary waste and higher total weight of the nacelles compared to a theoretical design value. A few of the key constraints in current casting technology are:

- Constraints in manufacturing do not allow designers to design optimally; the casting process is not able to reach wanted geometries. This adds much unnecessary mass to the finished nacelle as the largest part of the nacelle weight is cast iron.
- Variations in the casting process give very restrict requirements on quality control adding to cost and potential failures during the lifetime of the wind turbine.
- Contribution to greenhouse gasses when produced.
- With the size of wind turbines increasing the size of castings increase as well and the current foundry industry can have a severe challenge trying to accommodate the wind industry's needs over the coming years.

In order to improve this situation there are several approaches.

- Research into improving the manufacturing process "casting of large size items" to accommodate the industry's needs in the coming years. This will allow the wind industry to use ductile iron as a construction material for a longer time range and allow for improved efficiency of the nacelles and tower design.
- Further research into improved casting technology can improve the constraint in the design of cast items. A rough estimate is that an improved casting technology could

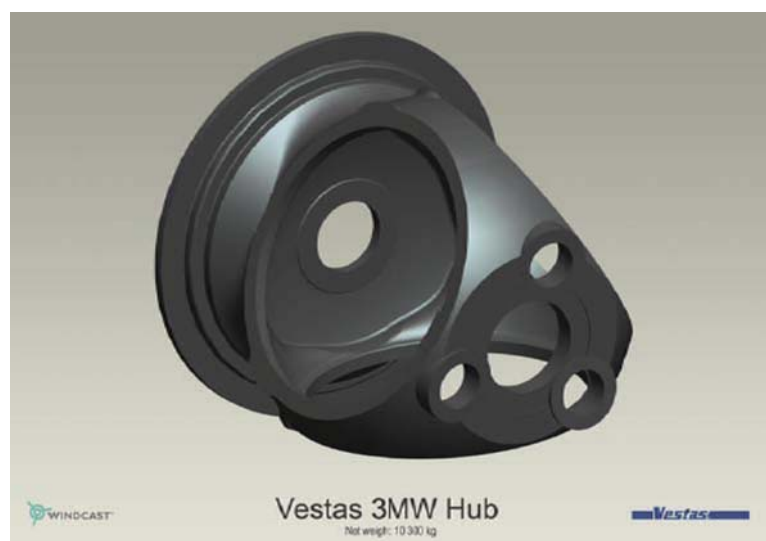


Figure 5: Rotor hub of a 3 MW Vestas machine (courtesy Vestas)

reduce the weight of the individual items with up to 25%. As the cast items represent upwards 60 % of the Nacelles total weight there is a large potential for reducing environmental and economic impact. Reducing the overall weight of the nacelles will lead to improvements elsewhere in the value chain as tower support can be reduced and installation cost reduced as well.

- Research into improved construction materials as alternatives to the currently used ductile iron grade. Improved construction materials should be lightweight construction materials that can be used in structural parts. This can cause a major shift in the nacelles design allowing for lightweight construction of the nacelle that will improve the overall manufacturing process of a wind turbine significantly.
- Stresses due to dynamic loads in a wind turbine are experiencing increased focus as this affects the reliability and lifetime of a wind turbine. Research into materials that are designed to handle stresses can improve the overall efficiency and reliability of the industry. In Denmark “REWIND - Knowledge based engineering for improved reliability of critical wind turbine components” (2011-2017) are funded by the Strategic Research Counsel and Industry. This could be used as the initial step into creating designed material for the structural parts in the nacelle.

2.6 Materials for the electricity generator and power converter

Iron, copper and all the other materials used for manufacturing magnetic steels and copper wirings for electromagnet generators are abundant in the world, come from a wide geographical distribution and have a world market which ensure transparent prices. This is not the case for the rare earth elements (REEs) necessary for PMG.

Copper is not considered a critical material. However, researchers alert that in addition to market and socio-political factors other factors including mining energy and water consumption and ground usage can turn copper into a critical element [102]. Leading copper producing countries in 2009 were Chile (34% of global production), Peru (8%), U.S. (8%), China (6%), Indonesia (6%), Australia (6%), Russia (5%), Zambia (4%), Canada (3%), Poland (3%), Kazakhstan (3%), and Mexico (2%); Mongolia and the Democratic Republic of Congo have major, recently discovered reserves [103].

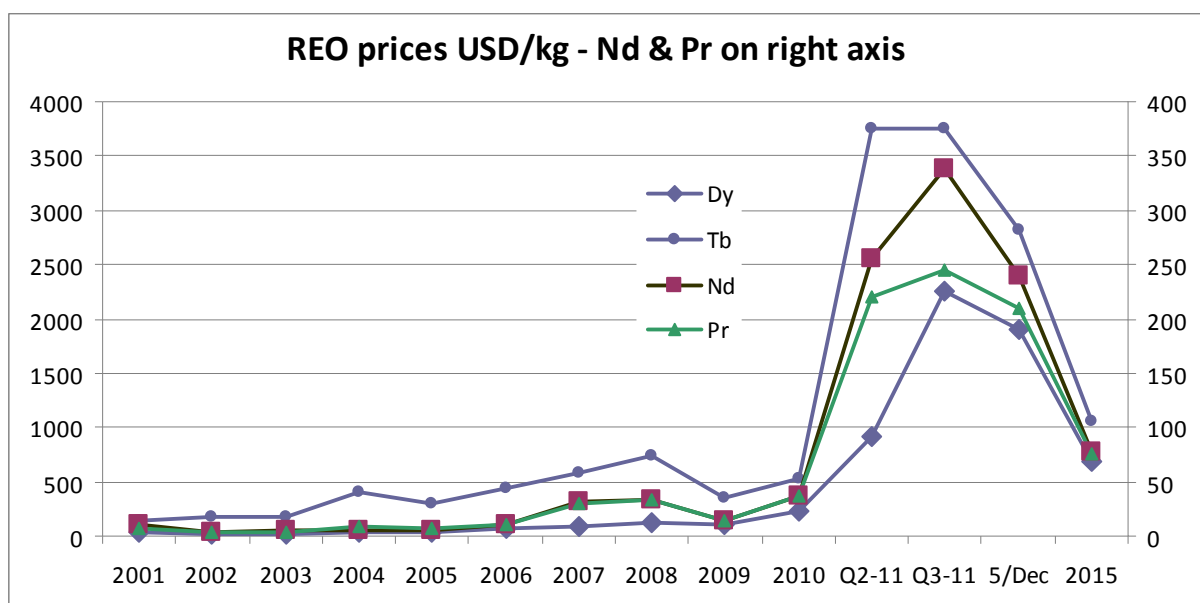


Figure 6: Price development of REEs used in magnets [114]. 2015 figures are Avalon's predictions [127]

REEs occur in low concentrations in metal ores, they are often co-produced with other metals and among themselves in concentrations which vary widely from ore to ore. The revenue stream from REE in those mines used to be a minor part of the revenue from the major product, and thus mine managers' decisions did not depend on the REE price signals from the market but on those of the main ore. However, recent scarcity (see below) and price increases are stimulating the development of REE-only mines or the re-opening of those in Western countries which closed in the 1990s because of the competition of low-price

Chinese REEs [3]. In effect, the cost of REEs used to represent a low percentage of the total cost of the generator which contributed to its demand being largely inelastic with respect to price. Therefore, even large changes in the prices of rare earths (Figure 6) had a relatively low impact on producer costs. As the same figure shows this has recently changed. Notwithstanding this, the rare earth industry expects prices to go back to more reasonable levels [127]

There are first signs that REEs for permanent magnets, and very specially dysprosium, are starting to be seriously scarce. This, in turn, suggests that client firms may have to invest in the extensive (and expensive) research and development (R&D) needed to identify substitutes and lowering the material intensity of REE in magnets. End-user strategies, i.e. by wind turbine manufacturers, are also affected and for example a technological option of a PMG in combination with a 1- or 2-stage gearbox (the hybrid model) is gaining more attention because of the reduced rare-earth content of the corresponding medium/high-speed PMG. On the positive side projections of new mines suggest that REE scarcity will ease for Nd by 2015 and for Dy by 2017 [126].

Once mined or coproduced, REE ore can be separated into a concentrate, processed into a mixed rare earth solution and elementally separated to oxides by solvent extraction. Rare earth oxides (REO) are ultimately used to produce rare earth metals, alloys and powders. REO production was estimated at 150 000 t in 2009, and recycling constitutes between 4 500 and 15 500 t [3, 104]. The vast majority of REE mining currently occurs in China (97 %), the rest in Russia, Brazil and Malaysia [3]. Chinese REO exports are restricted as shown in table 1. REO world reserves are estimated around 100 million t, of which 36 % in China, 19 % in the CIS, 13 % in USA and 5 % in Australia [3]. The demand for REO in 2008 was split between magnets (21%), catalysts (20%), metal alloys (18%), polishing (12%), glass (10%), phosphors (7%), ceramics (6%) and others (6%) [104]. Estimates suggest that by 2014 permanent magnets will be the main user of rare earth oxides (REO) with 30% of the demand [99].

Most magnets are manufactured in China (75-80 %) with Japan (17-25 %) and Europe (3-5 %) well behind [125]. Master patents on NdFeB magnets are controlled by two firms: Hitachi Metals (formerly Sumitomo)

	Export Quotas (t REO)	Change from Previous Year	RoW demand (t)	RoW supply (t)
2005	65 609	-	46 000	3 850
2006	61 821	-6%	50 000	3 850
2007	59 643	-4%	50 000	3 730
2008	56 939	-5%	50 000	3 730
2009	50 145	-12%	25 000	3 730
2010	30 258	-40%	48 000	6 700
2011	30 246	-7% ¹		4 410
2012	31 130	+ 3%		

Table 1: China's REE export quotas and demand from rest of the world (RoW) [3, 128].

in Japan and Magnequench, a former U.S. firm that was sold to a Chinese-backed consortium in 1995. Magnequench merged with Canadian based AMR Technologies in 2005 to form Neo Materials Technologies. It now operates as a Canadian-based company with Chinese operations [3].

Superconductor generators are based on coated conductors (CC) which is mostly made of yttrium, barium and copper (YBCO). The challenges include the development of low-cost industrial manufacturing for CC, an improvement in the performance of the cryogenic systems from 20 % today to 30 %, and a dramatic reduction of the cryogenic cost by a factor of 10 to reach 18 €/W at 70 K [108]. The magnetization method of the bulk superconductor and low AC loss superconducting wires or tapes for a superconducting stator are still under development.

Power electronics and in particular its main element in use in the wind industry, the IGBT, has relative short useful life (around 5-10 years), relative low power (a maximum of 1 MW), relative low junction temperatures (150 °C for the state-of-the-art); and are rated low voltage (below 1000 V). Those four elements represent specific challenges.

¹ The 2011 figure cannot be directly compared to the 2010 one because one additional category was included in the 2011 quota, ferroalloys. The figure of -7% results from a deeper analysis by Lynas Corp [129]

3. On-going research and actors in the field, and challenges

3.1 Introduction

World Wind Energy Associations [8-16] suggest that basic and applied research in the area of materials technology should focus on the development of structural and functional materials. Main wind turbines components made from structural materials include the rotor, nacelle machinery and tower, shall be characterised by low mass-to-strength ratio, and at the same time the cost of production shall be decreased as well. To fulfil these goals main basic and applied research challenges shall be focused on the tower top weight: rotor (hub + blades), drive-train, gearbox, generator, pitch system, nacelle bedplate, yaw drive and on the tower. For offshore turbines the support structure and transition piece have to be added to this list.

The EU sixth framework UpWind project [46] looks from this perspective at the design of wind turbines of 8-10 MW. Part of the research is even targeted at possible barriers that might be encountered when designing a 20 MW turbine with a rotor diameter of 256 m. The project RELIAWIND [91] focussed in general on the reliability of wind turbines and the development of related testing procedures.

3.2 Blades

The first large database for glass polyester and glass epoxy materials was the FACT database [47]. More recently the Optimat Blades project was executed during 2002-2006 [48]. In this EU 5th frame work project 18 partners from 8 EU countries collaborated and developed test methods and built the large Optidat data base [49]. One of the reports of the project formulates over 30 recommendations for testing blade materials. [50] The research of the Optimat Blades project has been continued and extended in the work package 3 of the UpWind project [46]. In this project the Optidat database has been further extended and research has been carried out with respect to micro mechanical modelling of fibre-matrix interaction. With respect to damage tolerant design and analytical models have been developed to be used in finite element analyses for fatigue damage simulation.

The parties involved in the research are all major blade material R&D organizations in EU and some large blade industries.

Next to the EU research and the national R&D programs, blade manufacturers are carrying out their own confidential research. Often a part of this research is carried out by one of the research organizations involved in the above mentioned EU projects. An example of such a research project is the Blade King project [51]. In this R&D project, supported by the Danish Advanced Technology Foundation, which is executed by LM Wind Power Blades and three other partners a completely new blade design is evaluated using new materials and manufacturing technologies.

Another important aspect being investigated is subcomponent testing. [52, 53]. Until now almost all material research is carried out using specially produced material coupons tested under mostly uniaxial and sometimes biaxial stress states [54]. However there is a very large gap between the material coupon (10 cm) and a real blade (50 m). Therefore it is very desirable to develop modelling and testing on different scales, where special subcomponents can represent parts of the total blade structure in which the stress states are comparable with the stress states in the actual blade part. In the WP 3 of the UpWind project [46] special attention was given to the development of a subcomponent to test the behaviour of the adhesive bonding paste.

Another research topic has and is being carried out in the work package 3 of the UpWind project with respect to non destructive testing. Non destructive testing can, if well developed, be applied to full scale blade testing giving much better insight in the behaviour of the tested blade than with just local strain and deflection measurements.

The parties involved in the UpWind material research are: DTU-Risø, WMC, Fraunhofer- IWES, CENER, CRES, VUB, UP, RAL, VTT, LTU, GE-Wind, Gamesa and ECN. Support to the design recommendation activities of the WP 3 is given by DNV and GL.

In the Netherlands a large R&D project on wind energy INNWIND [55] can be seen as the counterpart of the UpWind research.

In Denmark a centre on composite materials “Danish Centre for Composite Structures and Materials for Wind Turbines” (2010-2016) and a centre on reliability “REWIND - Knowledge based engineering for improved reliability of critical wind turbine components” (2011-2017) are funded by the Strategic Research Counsel and supported by the industry. Also a demonstration project “Experimental Research on Blades” (2011-2013) is starting up, supported by EUDP in Denmark.

In the USA similar research on glass and carbon fibre reinforced materials as in EU projects is carried out at Sandia Laboratories and Montana State University [56]. In the Asian countries the research is following the same lines as in the EU and USA but until now at a lower intensity. However for the near future it is expected that they will catch up with Western countries.

Research on the development and use of new fibres and matrices is being executed on novel concepts for hybridization and nano-engineering of fibre-reinforced composites. The development and use of novel fibres with ductile behaviour (opposed to brittle behaviour of carbon and glass fibres) is of particular interest as it is beneficial for improving composite toughness and durability. The fibres can, for example, be metallic, nano-engineered [116], natural, etc.

Nano-reinforced/modified matrices have high potential to improve fatigue properties of fibre-reinforced composites [117] and to add new functionalities

Confidential research with respect to fibre, resins and adhesives technology and production is carried out by all material suppliers over the world. New developments include new glass and carbon fibres with improved material properties, sizing formulations, and fibre matrix interface bonding. These new materials are confidentially developed in commercial research projects and they are tested in own laboratories and/or in laboratories at Universities and at R&D organizations.

With respect to core materials low price polymeric foams are promising alternatives. It is however very difficult to realize the exceptional mechanical properties of balsa wood without the help of nano-reinforcements and strong built in anisotropy in the foam cellular microstructure. Such technologies are, for example, now being combined/developed in the FP7 NanCore project “Microcellular nanocomposite for substitution of Balsa wood and PVC core material [115].

3.3 Tower and support structure

Onshore towers will be developed mainly in concrete or steel, or a combination of both. Compared to concrete, steel has thinner walls and can be welded. Fatigue, buckling and strength are the three main design parameters. And brittle crack resistance till -40°C is a pre-requisite. Increasing the material efficiency (ratio height / mass of the tower) requires innovative solutions to increase the bending moment and the fatigue life resistance of the assemblies to take benefit of much higher strength materials then currently used.. Different research projects recently completed or running are in this field. HISTWIN was funded by the Research fund for Coal and Steel (RFCS). The partners were TU Lulea, Sweden, Univ. Coimbra, Portugal; Univ. Aachen, Germany; Univ. Thessaloniki, Greece; Repower, Portugal; Rautarukki, Finland; Germanischer Lloyds, Germany. It aims at introducing higher strength steel in a tower through the introduction of a friction connection (assembly by bolts) between the sections of the tower. The steel considered in this project is S460 and S690 [89].

Safetower is another RFCS-funded project involving ISQ, OCAS/ArcelorMittal, Gamesa, ITMA, CSM, Leibniz University of Hannover, SIAG and Germanische Lloyd. In this project, alternative designs for the tower is considered, including on-site assembly. It is again considered to substitute S355 steel grade by S460M.

To increase the bending moment of the tower, one possibility is to increase the diameter of the tower, but it requires a design change to allow transportations of the parts until the site. Or use really high strength weldable steels with a yield strength up to 1100 MPa and high toughness up to -50°C . Lattice towers are investigated in this context. It will be also a part of the scope of the previously mentioned Safetower

project. Another alternative to increase the bending moment of the tower is use a composite wall. It is investigated by the University of Hannover to design a tower made of two steel shells, the space between the shells being filled with concrete, grout or polymer. Adhesion, complete filling of gap between the shells, assembly and inspection are however making this design a complex solution, although efficient from the material usage point of view.

Steel offshore foundations are heavy structures, generally with large wall thickness. Several research and development projects started mainly in United Kingdom and Germany. Most of these projects are demonstration projects (feasibility of a kind of structure) or are targeting optimised manufacturing of the structure. DeepWind (funded by FP6) is an example of the first kind of project where a floating wind turbine platform was developed. FabFound (Northern Wind Innovation programme), is an example of the second kind of project. And their Innovation Project is consolidating the activities of different actors. It should however be emphasized that none of the present projects focuses on materials, but on developing a specific generator with the existing technology.

The development of floating support structures are just in an emerging phase. A few demonstration projects are being carried out. One of the larger projects is the Norwegian Hywind project of Statoil [96]. Their application might be speeded up due to the deep water offshore plans in France. A challenge for the floating structures is the lifetime of the internal grid electric cables due to loads from the marine currents, support structure movements etc.

Concrete offshore foundations are reliant on weight and are even heavier than those in steel. Different companies and consortia have developed solutions and are searching to gain economies of scale through production of 100 or more bases. In the reported case study of Energy Efficiency and Renewable Energy SBIR Program from the US Department of Energy's office, [118] it is apparent that in order to build higher towers (to take advantage of stronger winds at higher altitudes) and to reduce cost of wind energy, three key issues should be addressed:

- weight scalability with height
- transport limitations and
- construction challenges

To overcome such challenges innovative materials and design concepts need to be explored. Lightweight composite towers could be an answer to these challenges. Some of the examples of research efforts into the use of light weight composite towers are:

- The Ohio Third Frontier Advanced Energy Program awarded project to fabricate composite wind turbine towers [119].
- The US Department of Energy recently awarded US\$8 million project on the development of materials and designs for deepwater floating platforms. The consortium will investigate options for using lighter, corrosion-resistant hybrid composite materials [120].

Research Challenges

Development of steel materials with higher strength/mass ratio, high fatigue strength, high toughness up to -50°C and stress corrosion resistance. The required thickness of the steel parts has to be over 30 mm and the material must be suited for welding such that the welded joints are able to withstand fatigue loads of over 90 - 100 MPa at 4×10^6 cycles.

Welding processes need to be developed and implemented with a very high efficient productivity. Welding techniques to be considered are: submerged arc welding, laser welding, gas metal arc (GMA) welding and hybrid-friction stir welding [59-88]. For the onsite assembly efficient field welding processes and bolted flange and friction connections need to be developed and implemented

To enable use of concrete support structures for larger water depths and very large wind turbines specialized pre-stressed concrete applications need to be developed.

3.4 Transmission

Concerning the steel transmission components cooperative projects are running in the various financing frames at European level. PROTEST [90] concerned in general the reliability of high-power transmission and mechanical interfaces and the development of testing procedures, while X-GEAR [92] is devoted to geared drive trains, focusing in particular on new materials (e.g. advanced sintered steels, nano-powders) and new surface treatments (e.g. flame spraying, laser shock peening, laser ablation, laser alloying, laser re-melting, PVD, Electron Spark Coating).

The design of materials with extreme strength-to-mass ratios and advanced control and measuring systems geared towards the highest degree of reliability, and critically, reduced overall turbine mass are addressed in the UpWind project [46].

The main research actors within Europe are associated in the German association Forschungsverein Antriebstechnik (FVA). A handful of research centres and universities have specific competence regarding transmission technology.

Challenges

Material alloys and surface and heat treatment

The gearbox with case carburized gears has established itself as a proven concept. The main causes for early failures -such as gray staining and micropitting- are now understood and can be solved. Challenges for the future are to design cost saving alternatives, which can be realised by:

- Removing cost increasing factors such as alloying elements in steel.
- Increasing the power density of the gearbox by alternative designs and using materials with a higher fatigue resistance.

In order to develop materials solutions with a higher endurance limit, a deeper and more diffused scientific, technological knowledge on various topics with respect to material alloys and heat and surface treatments is needed. The surface treatment topics include techniques such as laser texturing or hardening, metallic and non-metallic coatings. Steel producers should focus on the reduction of endogenous non-metallic inclusions and the elimination of exogenous inclusions, which may cause occasional but catastrophic failure. This can be reached by improving production technology as well as non-destructive test methods.

New developments shall be screened with existing test procedures for scuffing and micro-pitting resistance, lubrication behaviour, solid contaminant influences and so forth. On the other hand the test methods and design rules must be adapted to larger devices.

The challenges for cast components are comparable to those of the nacelle bedplate and rotor hub, except that besides EN-GJS-400-18-LT also other grades are used. This includes extrapolation of material properties to large wall thicknesses, design rules including the effect of casting defects, reliable welding repair procedures, the development of higher strength grades, resistance in cold climate conditions etc.

To reduce the weight of the castings, alternative materials for the housing can be an option. An example of such a development is the project “Lightweight Turbine Gearbox” funded by the Northern Wind Innovation Program. The target of this project is the reduction of the weight of a gearbox by replacing the cast iron of the housing with aluminium that is additionally reinforced with the fibre reinforced composites [121].

Manufacturing aspects

The life time of gearboxes and bearings with given load conditions not only depends on the materials used and the surface treatments applied, but is also strongly influenced by the manufacturing techniques used to produce the contacting surfaces of the different components. Therefore further research challenges are related to influence of grinding machines on the surface topology and the degree of surface finishing required to reduce incidence of micro-damages for the different applied materials.

Alternatively, research should be directed towards alternative designs of gears and bearings, including a bearing rating procedure that takes the influence of white etching cracks and micro-damages on the expected life time into account.

Lubrication

Current lubricants are based on mineral oils, but there is a tendency in the lubricant market to move to ecolubricants. Recently the European Ecolabel for biolubricants was updated to include lubricants for transmission. Wind energy is one of the markets where this type of lubricants should be introduced in order to enhance their environmental performance. From this perspective there is an urgent need for developing alternative oil formulation for transmissions, especially because the viscosity requested for this application is high in relation to other industrial gears.

Damage testing and condition monitoring

Standard test methods need to be developed to simulate the damages from in-field observations on lab scale. Test methods and test rigs are required to screen in a cost-effective way designs, lubricants, surface treatments and coatings.

For condition monitoring, improved gearbox damage sensors and monitoring strategies are required for early damage detecting and lubricant monitoring under operational conditions.

3.5 Nacelle bedplate and rotor hub

For the heavy steel components current research is directed on application of high strength low alloy steels to increase strength properties and decrease the weight and cost of production. Now-a-days typical welded structures are made from steel S355 NL (Yield Strength = 345-355 [MPa]). At the same time leading European steel producers are supplying e.g. crane industry with HS steel plates made from really high strength steels: plates – S620 QL up to S 960 QL and even S 1100 QL and S 1300 QL (WELDOX 1100 – plate thicknesses = 4,0-25,0 [mm], WELDOX 1300 plate thicknesses = 4,0-10,0 [mm]).

Involved EU-industries are: SSAB Oxelosund AB. Sweden, Masteel UK Ltd. United Kingdom, Ruukki Finland, Tata Steel United Kingdom, DanSteel Denmark, ArcelorMittal Luxembourg, Thyssen Krupp Stahl Europe, Salzgitter AG Germany and UnionStal Poland.

Castings

The weight of cast item parts are adding to cost through: needed tower size, manufacturing, amount of material needed, transport, installation, decommissioning, and recycling. The mathematical prediction/simulation of casting processes is state of the art and continuously developing. But the physical casting process is to a large extent an up-scaled version of what has been used for hundreds of years. Current foundry technology and industry capacity is not able to support future casting needs for wind turbine industry, this primarily being a size, quantity and quality issue. Today the geometry is given by the manufacturing process and not by the designer. This is leading to a future constraint in the manufacturing process as items sizes and quantities increase.

As weights increase hereunder blades, the dynamic loads in the structural parts become more and more important. Increased research of how the stress state is under operation and how more “intelligent” materials can support a future design of wind turbine components.

Alternatives to ductile irons are required in order to make more cost effective wind turbines in the future. Within a few years rotor hubs will be produced that are close to 100 metric t in weight if the design is not changed dramatically. Only a few foundries worldwide are able to produce this and usually only as single piece production not as serial production. This could potentially be a major constraint in the industry.

Research challenges

Development of new materials with higher strength/mass ratio high fatigue strength: (basic and applied research)

- HSS of yield strength > 1000 [MPa] and to endure fatigue stress cycles at least 4×10^8 , high toughness up to -50°C , for HSS plates of thickness up to 100 mm,
- high strength cast steel alloys,
- high strength cast ductile SA irons,
- high strength aluminium and magnesium alloys,
- Metal Matrix Composites.

Production processes of heavy bedplates and rotor hubs: (basic and applied research)

- Raw high strength alloy steels and ductile irons castings,
- New materials, ductile S.G. irons and high strength alloy steels casting+ welding procedures of parts of raw casts,
- HSS steel thick plates forging plus welding procedures,
- High strength aluminium and magnesium alloys pressure casting+ plus welding procedures,
- High strength aluminium and magnesium alloys thick plates rolling plus welding procedures,
- Reinforced materials thick plates of Metal Matrix Composites plus welding procedures.

3.6 Electricity generator and power converter

Electromagnet is a very established generator technology with few possible breakthrough research proposals. Exploratory wire research aims at increasing conductivity through nanotechnology e.g. the Ultraconductus project [105].

The general lines for permanent magnet research focus on performance, cost and recycling. Performance research include higher energy products (discovery of new materials); better high temperature performance (substitution/use of additives); higher electrical resistivity (e.g. reducing eddy current losses/use of additives); and enhanced mechanical properties (additives/processing). Cost-related research focuses on raw materials costs; decrease or eliminate RE constituents (new materials/nanoprocessing); and processing costs (direct conversion, selective separations). Finally, recycling research approaches include manufacturing scrap – swarf (processing/selective separations); and post-consumer (processing) [104].

Ongoing research aims at reducing the REE content of magnets e.g. by substituting REEs e.g. at the grain boundaries [93]; increasing their efficiency, magnetic density and temperature range. This is partly done by searching alternative materials. Basic science research focuses on the synthesis of highest quality polycrystals and single crystals, advanced characterization methods, especially neutron and magnetic X-ray scattering and first principles modelling (Ames Laboratory, US); anisotropic magnets based on the high-temperature, rare-earth-based alloy previously designed for isotropic bonded magnets (Ames); bulk nano-structured magnetic materials (General Electric –GE- in the US). Applied research includes higher-flux density PM generators (QM Power in the US), magnets based on Fe-, Co-, or Mn-rich materials (Univ. of Delaware, US); 640 kJ/m^3 and 80 % less rare-earth mineral content (GE in the US); gas-phase-modified TM materials and FeNi phases with the L10 structure (both at Tohoku University, JP) [93]; high-performance anisotropic nanocomposite PM with low RE content (Hitachi in JP).

Japan's Rare Metal Substitute Materials Development Program targets a 30 % reduction in the Dy and Nd content of PM through grain refinement and nanostructure techniques, and REE-less/free alloys or other elements. Korea has developed since 2007 a comprehensive research programme supported by an annual budget of one billion USD.

The main research institution in Europe are the Materials Innovation Institute (M2i, NL); Leibniz Institute for Solid State and Materials Research, Dresden (DE) Institut Néel, Grenoble (FR); Trinity College, Dublin (IE); St. Pölten University of Applied Sciences (AT); Vienna University of Technology (AT); Jožef Stefan Institute, Ljubljana, (SI); Vakuumschmelze, GmbH, (DE); Siemens GmbH, (DE).

Applied research and demonstration include direct current (DC) generators which reduce the mass of the active part of a DD-PMG by up to 25 % [109]. Incidentally, a DC generator in a DC wind farm grid has the potential to increase output by reducing losses from AC/DC/AC power conversion.

Superconductor research includes reducing the cost of wires: more efficient processes to deposit the layers of YBCO ($\text{YBa}_2\text{Cu}_3\text{O}_7$), the superconducting cuprates that form coated conductors (Riso). Specific HTS research projects include Risø's Superwind project (DK); Converteam/Zenergy research on an 8-MW HTS generator; AMSC/TECO Westinghouse on components for a 10-MW HTS generator.

Power electronics research focus both on voltage, materials and on new control strategies. The increase in IGBT junction temperatures is subject to much research. Whereas the current industry standards is 125 °C, new state-of-the-art series offer up to 150 °C which translates either on a 20 % increase in power for the same size, a corresponding size reduction, or a trade-off between both [2].

Silicon carbide (SiC) is being investigated as a base material for IGBT and other switches because it has the potential to dramatically increase the power density of the power converters [110], and therefore to be a breakthrough. Several research projects in the US are investigating SiC switches (IGBTs, thyristors) up to 15 kV e.g. within the concept of a transformer-less intelligent power substation (TIPS) [112]. One of the main focuses of this research is to reduce the production costs to make it competitive.

4. Materials specification targets for market implementation in 2020/2030 and in 2050

4.1 Specification targets for market implementation in 2020/2030

To realise the international targets for the implementation of wind energy both on- and offshore wind energy must become economically competitive with fossil fuel and nuclear power generation. Therefore the current trends, the scaling up of the wind turbines, see Figure 7, and of wind farms, needs to be continued in the considered time frame. To achieve the required reduction in investment and maintenance costs, breakthroughs are required in the technology development of wind turbines. Especially for offshore wind the need to reduce investment, operation and maintenance costs puts high demands on reliability, accessibility and operation and maintenance strategies.

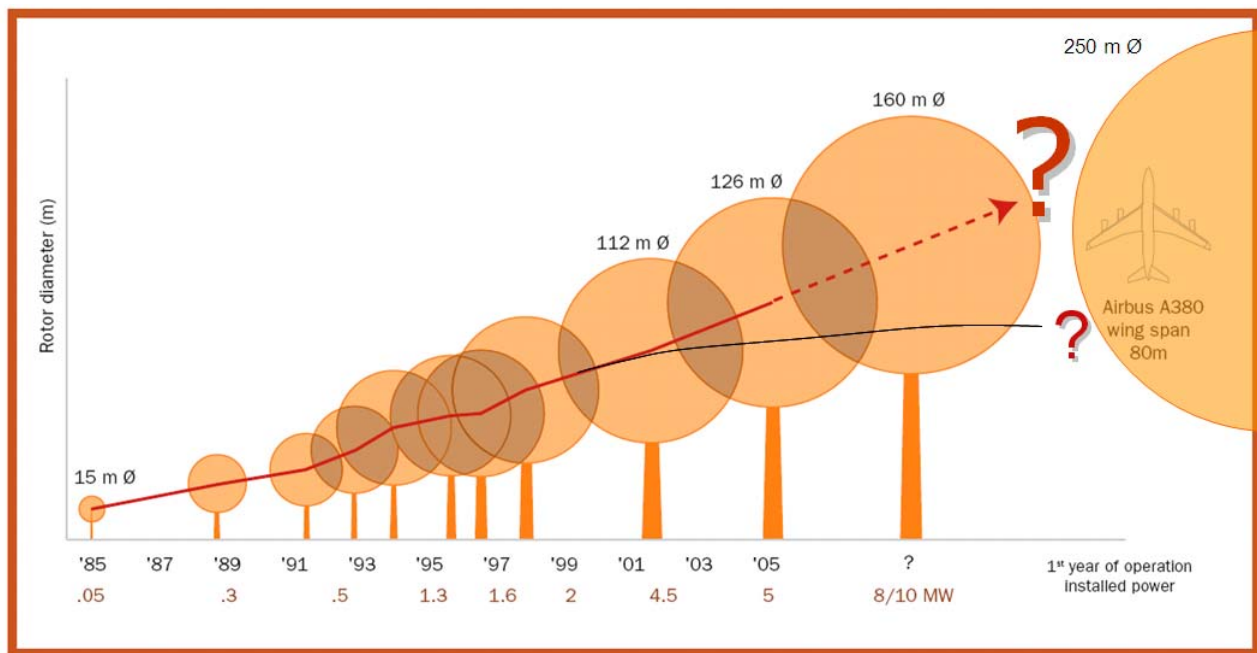


Figure 7: Turbine sizes at time of market introduction [11]

Achieving the required high level of reliability and availability of almost 100% requires condition monitoring of all critical components. Via this condition monitoring preventive, well planned, maintenance can be carried out in periods of average low wind speeds when power generation losses are relatively low.

To lower the initial investment costs all components must be optimised with respect to functionality and material consumption. New functional and structural designs must be considered that put higher demands on reliability of the design process and the materials used.

Since wind energy is a renewable energy source the recyclability of all components has to be strived for. For most of the metallic components this has already been achieved nowadays. However for a number of other parts like electronic components and especially the blades this is not yet the case. For the development of the electronic components wind energy can probably rely on the developments in the large world market of this type of components, since these are used in a lot of other applications too. However for the blades this has to be specifically a wind energy development. Since no other technology uses fibre reinforced components with the size quantity and wall thickness as wind turbine blades do.

4.1.1 Blades

The overall target for future blades is to improve the reliability and performance at lower costs. This requires improvement of the material in order to optimize the interaction between fibres, sizing and resin,

the fibre architectures, the laminate design. The manufacturing processes must be reliable and reproducible and the overall structural design of the blades must be thoroughly thought out.

Also the sustainability aspect is in focus. Use of natural resins in combination with fibres based on celluloses fibres extracted from wood, bamboo, sisal, coco, flax, hemp, jute, straw plants etc are in focus especially for use in smaller size WTGs. The targets for the blade materials and production technology for 2020/2030 can be summarized as follows:

- In the near future the main challenges will be related to the current materials used for blade production. Specific challenges are:
 - To improve material models to allow for more accurate and reliable design analyses, including detailed fatigue damage analyses and probabilistic strength analyses,
 - To draw up specific wind energy material testing standards to describe how to accurately measure the material properties,
 - To set up and improve models based on damage mechanics to describe effects of production defects and imperfections on the blade performance,
 - To come up with blade substructure test specimens to fill the gap between large scale blade testing and small coupon testing,
 - To development in service condition monitoring techniques for blades.
 - To increase the production volumes required by the ever increasing market demand.
 - To lower the production costs.
 - Improve coating technology to increase the sand and water droplet erosion, the UV light resistance, self cleaning capability and ice shedding efficiency in cold conditions
- In the longer run there is a need for improved materials for lightweight blades. The materials are needed also to allow for the faster production of blades. The lightweight blades will allow the design of very large turbines without the consequences of too high gravitational loads. Low weight blades not only will reduce the loads on the blades, but will also have beneficial consequences on design of the hub, the main shaft and the other load carrying parts. The material to be considered can be using high performance glass fibres, carbon fibres and/or hybrid reinforcement combining glass and carbon fibres, and by an intelligent design of the fibre architecture as modelling results from the UpWind work package 3 group show high potential for fibre bundle arrangements. [94]
- The distributed control options for blades will lead to new structural designs of blades. A big challenge for the 'smart blades' [57] will be the required high level of reliability at a very low maintenance level and the possibilities of the new devices to withstand lightning strikes,
- A further challenge is the recyclability or the reuse of the blades. The currently used thermosetting resins cannot be recycled. Thermoplastic resins offer however more great opportunities for future blade designs [58]. Blade can become more easily recyclable; the design can reassemble the design of airplane wings, with spars and ribs, and thus lowering the weight of the blade considerably. Furthermore the material offers potential for serious cost reductions and reduced production cycle times. The main hurdles to overcome is the processing temperatures ($>180^{\circ}\text{C}$) and the infusion processing performance (high viscosity) of the thermoplastics. Other challenges are creep behaviour, the required fibre content and the design of the bolted connections. Hence, using these resins requires switching to completely different production processes where blades can be produced in parts. Spars, ribs and skin that are joined together without the use of adhesives by fusion bonding or welding. These design challenges offer next to this good possibilities for incorporation of structural health monitoring and built-in of distributed control devices and sensors.
- Development of biopolymers replacing the organic mineral oil based resins. These resins made from biological products also link to a vision for the longer future.

All improvements addressed above should lead to:

- Blades that operate reliable during the full life time of the turbine,
- Reduction in blade weight of 30-50%,
- Reduction of costs
- Full recyclability or reuse of the blades,
- Applicable condition based maintenance.

4.1.2 Tower and support structures

In the short term, the onshore market will mature and replace generators at existing sites. To increase the efficiency of onshore wind, wall thickness of the structure must be reduced and higher height should be reachable. Decreasing the wall thickness requires the development of higher strength materials, combined with increasing the bending moment of the tower with a composite solution or with stiffeners. This will be possible if fatigue performance of the assembly (including welds and welded joints) is not impaired by the decreased thickness. Improvement of the welding techniques and eventual post-treatment of the welds and welded joints allowing extension of fatigue life will be required. More specifically, it means that the joints should be able to withstand a stress above 90 MPa at $2 \cdot 10^6$ cycles. Analogous efficiencies should be sought in concrete towers, whether they be formed from pre-cast concrete rings or cast in-situ using specialised formwork.

For steel offshore foundations, the main specificity is the wall thickness of the support structure. Decrease of the cost of the support structure can be achieved by decreasing of the wall thickness, with problems similar as for tower (decreased wall thickness, application of higher strength material, fatigue life of the assembly) and by decreasing welding costs (synergy – lower thickness - lower welding cost). The last item can be achieved and improved by applying more efficient higher quality welding technology. In this category one can mention the non vacuum electron beam technique and friction stir welding developed by TWI, laser hybrid welding or the welding at very high heat input using conventional submerged arc welding. Specific steel developments will be required to develop thick gauge materials (thickness >40mm) with adequate toughness (K_{JC} above $100\text{MPa}\cdot\text{m}^{1/2}$ at -40°C) when welded at very high heat input (above 5kJ/mm).

Other material targets are:

- $YS > 355\text{MPa}$
- K_{JC} above $100\text{MPa}\cdot\text{m}^{1/2}$ at -40°C
- Toughness guarantee in HAZ even for welding with very high heat input (above 5kJ/mm)
- Fabrication process optimisations, production facilities including automations etc. Yield for both steel as concrete components (not quantified)

For concrete off shore foundations the main target is to optimise concrete properties relative to cost, together with establishing factory construction processes to minimise overall cost.

4.1.3 Transmission

The specifications of transmission systems are more and more demanding as the turbines grow in size. The most important parameter is the torque to be transmitted, and this is largely depending on the technical design concept of the wind turbine. The load spectrum contains torque variations expressed as magnitude and frequency occurring over the entire operating life of a turbine. Based on this load spectrum, the transmission gearing is dimensioned by the manufacturer in such a way that the fatigue-strength limit has sufficient clearance above the load spectrum [92]. In addition it is mandatory to deal with the phenomenon of drive train vibration in wind turbines, i.e. the most important natural frequencies and modes of vibration have to be tuned to avoid resonances. [95].

For a 12 MW wind turbine in a strong wind regime in 2030 the torque is estimated at 15 000 kNm, and the total mass of the gear unit should be less than 180 t. In order to reach these goals materials development should be complementary to the design options which will be pursued.

4.1.4 Nacelle bedplate and rotor hub

The challenges for the cast components relate to the material properties and the production processes.

Improvements in both must lead to lighter, more rigid and more cost efficient castings. In order to achieve that the following R&D targets should be addressed:

1. Modernize foundry technology to allow more precise casting to original design. Weight savings up to 25%,
2. Remove costly production flaws i.e. micro structural flaws, porosities, geometrical deviations,
3. Remove unwanted residual stresses causing break downs in operation of WT,
4. Eliminate incorrect mechanical properties in tensile strength, fatigue strength, yield strength, elongation, impact toughness, and hardness,
5. Improve reliability of casting process to avoid waste, this through increased development in:
 - Mould technology (including coatings and engineering design tools)
 - Gating/filling technology
6. Superior variants of ductile iron or related casting materials. There is a high potential in other cast iron grades with improved mechanical properties or in combining casting and forging techniques to further enhance needed properties.

4.1.5 Electricity generator and power converter

Parameters to define specifications:

- Direct-drive generators:
 - Weight - a 12-MW direct-drive generator below 170 t by 2020, below 130 t by 2030. Current estimates put a 10-MW PMG at 300 t, AMSC initial data suggests 120 t for similarly-sized HTS technology.
 - Specific cost should be an indicator but information on price is highly sensible, which makes this indicator difficult to use.
- Permanent magnets: specifications for commercial magnets (military magnets have higher grades)
 - Power density range increasing from 270-422 kJ/m³ in the most performing magnets of today to 360-500 by 2020 and 460-535 kJ/m³ by 2030.
 - Remanence (H_{cj}) and coercivity (B_r).

For the purpose of setting future magnet specifications the highest performing magnets from several manufacturers were plotted in a H_{cj}/B_r curve which we call $H_{cj(2010)}$ (see Figure 8) The function that relates them was found to be linear ($y = A x + B$) and therefore it conveniently reflects the trade-offs among these two key parameters of a permanent magnet. The values of this function are:

$$H_{cj(2010)} = -5.5581 * B_r + 9.2671$$

In this equation and Figure 8 H_{cj} is expressed in MA/m and B_r in Tesla respectively. Future specifications of this relationship are reflected in that figure for 2020 and 2030.

- Rare earth content (in mass) at equal magnetic density: neodymium (31 % currently, 28 % by 2015, 25 % by 2020 and 20 % by 2030), dysprosium (2.3 % today, 2 % by 2015, 1.8 % by 2020).

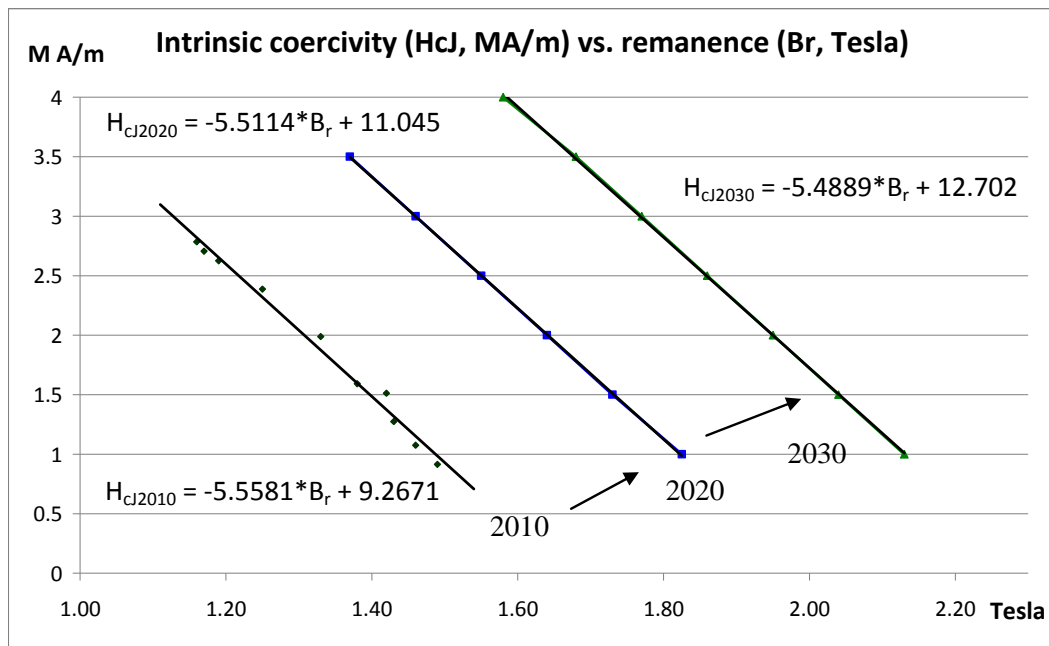


Figure 8: Proposed specifications for key permanent magnet parameters by 2020 and 2030

- Power electronics devices:
 - Junction temperatures - e.g. for IGBTs from today's 150 °C raising to 200 °C by 2015, 225 °C by 2020;
 - Current rating to 330 A by 2013, 500 A by 2020.
 - Voltage: from today's low voltage raising to 6 kV by 2013; 15 kV by 2020, 25 kV by 2030.
- Power converters:
 - Voltage will need to match medium-voltage generators, a big change given that the current offer is at low voltage, i.e. below 1000 V. Power electronics (e.g. switches) and cables will need to adapt to medium voltage without a significant price increase or loss of performance.
 - Topologies: 3-level converters and other more developed structures.
- HTS
 - Superconducting wire cost – 300 €/kA-m today to 30-40 €/kA-m by 2020 and below 15 €/kA-m by 2030
 - Superconductor temperature – 70 K today to 85 K by 2015 at laboratory level and by 2020 in the market.

Reduction of component mass has the knock-on effect of enabling the optimisation and consequent materials and mass reduction of supporting structures (e.g. the bedplates, nacelle, tower, foundations). Work by Converteam [35] suggests that an 8 MW, 12 rpm design multiplies nacelle mass savings by up to four times in the tower and offshore foundation structures. In addition, components have been treated here separately but the union of them, e.g. power electronics integrated in the generators, offers further possibilities for using less materials.

4.2 Specification targets for market implementation in 2050

Due to the developments up to 2030 wind energy will be competitive with fossil fuel and nuclear energy generation. The size of offshore turbines will be about 12 MW, onshore the turbine size will be smaller due to the fact that these have to fit into the landscape. In fact wind energy has become a well accepted and economical option for energy generation.

The deployment rate of wind energy will, according to the available scenarios, be stabilized at 50 GW per year in the period 2030 to 2050. Of this, especially in Europe, a large part will be installed offshore since the available space on land is a limiting factor.

Floating structures will be needed if the high wind potential of deep water is to be realised. The size of the turbine could grow to 20 MW and the targeted service life could increase to 25 to 30 years to make the offshore installations competitive and cost effective.

Of course recyclability of the whole wind turbine needs to be realised. Therefore material developments will be required to decrease further the environmental footprint of wind turbines.

4.2.1 Blades

Wind turbine generators with diameters approaching 250 m and nominal power of 20 MW are not unrealistic goals. Based on classical scaling relations these very large blades would weigh upwards of 150 t each. The challenges in the design and production of such large components are therefore reduction of weight, modular construction of the blade to be assembled on site, maintenance and inspection based on structural health monitoring. These goals cannot be achieved without improved fibre architecture combining the stiff and strong but more expensive high performance carbon fibres with high performance glass fibres (e.g. s-glass type) replacing the commonly used low cost E-glass fibre. Hybrid material combinations are in this technology of big potential and big challenges for the researchers. However the pressure on price reduction will continue to be very high.

The small and medium sized turbines are not expected to be out of the market. Requirements for low cost of small and medium sized wind turbines will require an assembly line production of blades with robotic control of the manufacturing. Hence the reliability of the materials and the production processes must be very high.

Recycling of worn-out blades is expected to be part of a life cycle requirements. For example the “back to sand” use of the glass in cement production. Possibilities for re-use of blade and blade materials in lower performance requirements will be part of inspiration to future innovative initiatives. For example a worn-out blade could be used as floating anchors in wave energy plants. Alternative blade materials achievable for instance natural fibres in thermoplastic resins or in biopolymers will also result in more and better recyclability.

4.2.2 Tower and support structures

A longer term prospect is the development of floating offshore wind energy convertors. These convertors will be more remote from the shore and have heavier structures, which will make likely economically viable only for very large generators. The technological trends are expected to be similar to the one encountered in the shorter term. Therefore the R&D challenge shall be directed on the development of very rigid and fatigue resistant designs of towers, of new very high strength structural material characterised by good weldability and of high quality, high efficiency and low cost shop and erection welding technology e.g. hybrid laser welding, friction stir welding and electron beam welding.

4.2.3 Transmission

The performance level expected in order to allow the exploitation of the 20 MW technology requires a significant improvement in the power density of the drive train. For example, for a 20 MW wind turbine with a torque of 35 000 kNm, the total mass of the gearbox should be less than 400 t.

In order to reach these goals, materials development should be complementary to the design options which will be pursued.

4.2.4 Nacelle bedplate and rotor hub

To save weight in the nacelle and as a consequence in most of the other structural parts of the turbine, designers must have the opportunity to choose from a large range of light weight construction materials that allow a strong and slender design. These materials must be priced competitively, and have excellent strength and fatigue properties.

4.2.5 Electricity generator and power converter

Weight of a 20-MW direct-drive generator below 200 t by 2050. This should be possible with HTS.

Development of low-cost manufacturing processes for coated HTS.

Large IGBT or similar devices able to handle 20 MW generators at voltages above 20 kV and with junction temperatures above 250 °C.

5. Synergies with other technologies

With respect to the blade materials, in the energy sector synergies can be seen with solar energy, where, depending on the specific application, huge high strength/low weight scaffolds are required. Also synergies with wave energy plant are obvious for the huge floating structures. In aircraft industry very high level fibre reinforced materials are used. This high cost performance is inspiration for the blade application and can be implemented in blade technology. Also the ship industry uses large quantities of fibre reinforced materials and experience can be used in offshore applications although the loads on the structures differ from those in wind turbine blades. The use of light and strong composite materials is also increasing in the automotive industry. Weight saving together with the use of damage tolerant and impact energy absorption and recyclable materials is essential and competitive in the automotive sector. These developments show a high potential synergy with material developments for wind turbine blades, although the scale is completely different.

Making towers and support structures is very close to the making of components for civil engineering work and pipeline production. It can be expected that any advance in the development of wind turbines could affect the development of civil engineering, and vice versa. Similarities are also present between offshore foundations and the construction of offshore platforms from the oil and gas sector. In fact, many problems have already been overcome: corrosion and bio-corrosion protection, fatigue behaviour, management of the structures including the floating ones are already real solutions needed to be adapted to the new different wind applications. The materials used, concrete and steel, and the environmental conditions are similar and many of the manufacturers and contractors apply their offshore oil and gas and civil engineering experience in the wind sector. For instance the heavy lift vessel Svanen was designed and built to construct the Storebaelt Bridge in Denmark and it is now used for the installation of monopoles for wind turbines.

Transmission components (gearbox, bearings and shafts) present synergies with sectors including the surface treatments, lubrication, coatings developed for aerospace, aeronautics and ship propulsion applications.

The castings of the hub and nacelle are close to the heavy frames of ship-diesel engine housings and the steam turbine and generator housings from large electricity plants. Although the strong requirement to reduce the weight and to improve the performance are less prevailing there.

Wind turbine generators, whether electromagnets, permanent magnets (PM) or high-temperature semiconductors, present synergies with sectors using generators or motors including hydropower, marine currents, cogeneration, vessels (generation and propulsion); train traction; and industrial sectors (pumps, fans, crushers, mills, rolling motion, shredders, etc.). Of utmost importance are synergies with the electric vehicle sector because of its projected development: according to DoE projections electric vehicles demand of neodymium (Nd) will outweigh wind turbines by 4 times by 2025, and of dysprosium (Dy) by 3 times [3]. Beyond this all industrial uses of motors, other power generation subsectors, and propulsion machines (e.g. for ships) present strong potential synergies with the wind energy sectors. Other sectors competing for rare earths include catalysts, NiMH batteries electronics, glass, ceramics, metal alloys and laser technologies [111]

The manufacture of PM from rare earths presents few synergies because of its specific manufacturing process. Those synergies would include other metal-oriented manufacturing processes

The synergies of power converters are high with rail traction and industrial converters. In addition, being a electronics device, improving in electronics devices for any industrial and consumer field could eventually result in improvements in power converters.

6. Needs and recommendation of activities addressing 2020 and 2050 market implementation

6.1 Needs and recommendations for market implementation in 2020/2030

The European Wind Initiative (EWI) is the high-tech roadmap to reduce the cost of wind energy. Its implementation will pave the way for the large-scale deployment of wind energy worldwide, and secure long-term European technological and market leadership. The EWI will take the European wind industry to the next stage. It will develop the wind energy technology of the future, the necessary testing facilities, and streamlined manufacturing processes. The European Wind Initiative prioritises the following technology areas: new turbines and components, offshore technology, grid integration, resource assessment and spatial planning. There is the clear need to address activities on the material/technical issues as mentioned in the chapters before.

A deeper scientific and technical inter-platform information exchange will strongly contribute to create a common language still not existing at current time among the various expertise involved in the wind issues. Exchanging of technical experts, preparation of workshops and seminars as well as presence of opinion leaders, managers and decision makers either in the Advisory Board and/or Steering Committee shared in a common way among different platforms will feed such an inter-sector, inter-material cooperation.

The EWI roadmap composed the as main targets:

- To make wind energy the most competitive energy source on the market during the decade 2020-2030, and as a first step decreasing the wind energy costs by at least 20% by 2020.
- To enable the required large scale deployment and grid integration of wind energy offshore and onshore with the aim of reaching wind penetration levels beyond 20% of European electricity consumption in the early 2020's
- Ensuring the European technology leadership on- and offshore, and developing large offshore wind turbines, including exploring concepts up to 20 MW.

Based on these targets the following activities, with respect to the materials used in current wind turbine technology, have been have been distracted

6.1.1 Blades

The main challenges related to the currently used blade materials are related to stiffness optimisation, fatigue life and damage prediction methods. The development of models and verification test procedures to be used in the design process of blades are important parts of this perspective.

To address the challenges on the short term the following R&D activities (*basic and applied research, pilot actions*) are recommended:

- Further development of micro- and meso-mechanic modelling on fibre/interface and on fibre arrangement level in order to optimize materials architecture and to establish virtual mechanical testing possibilities.
- Extension of the current phenomenological and analytical material models based on damage mechanics to include effects of manufacturing defects and fatigue damage on the complex stress states notably in blades. These models aim to enable more accurate and to the limit blade designs, including fatigue damage evaluation, strength degradation and probabilistic analyses. Using this type of design tools will have the purpose to the lowering of the required safety factors and more reliable blade designs and lighter blades.

- The development of subcomponent modelling and testing methods to fill in the gap between coupon testing and full-scale testing. This can result in an 'Atlas' summarising the static and fatigue behaviour of a large variety of blade design details, as applicable for the current blade designs.
- Extension of the existing databases (e.g. Optidat [49]) so that they cover the mechanical properties of the large variety of the materials used in blades. Also the databases should include effects of aging, temperature and loading rate effects
- Systematic research into the influence of manufacturing methods with the aim to speed up production cycles and to ensure a reliable production of blades.
- The definition and draw up of blade material testing standards, that will allow researcher to compare testing results produced in different laboratories and the manufactures to test their material data in an efficient and consistent way.
- Research on the condition monitoring and other non-destructive testing techniques to monitor blades during their life time. These non-destructive testing techniques can also be used for monitoring blades during the full scale blade tests for certification purposes.
- Research on coating technologies to decrease the sand and water droplet erosion and to increase the UV light resistance, self cleaning capability and ice shedding efficiency in cold conditions.

To address the challenges on the longer term that need to enable to production of light weight high performance blades activities are needed in the field of:

- Development and improvement of materials, including novel concepts for hybridisation and nano-engineering, that combine high strength, high stiffness and toughness and fatigue resistance. These materials however should not degrade in the wind turbines life time due to effects of aging, temperature variation and moisture (basic and applied research).
- The development of a very light weight core material that performs better than balsa wood and PVC foam required for the production of very large blades (pilot and basic research).
- Development of assembly line production of blades with robotic control of the manufacturing and quality control (pilot and demonstration actions).
- The structural layout of blades that allow in combination with the above mentioned materials the design and manufacturing of blades up to 90 m in length to enable the economical realization of 10-12 MW turbines (pilot and demonstration actions).
- Development of applicable condition monitoring techniques that allow for a condition based maintenance strategy (pilot actions, demonstration actions).
- Development of recyclable materials like natural fibres and thermoplastics that allow for cost efficient light weight blade designs. Thermoplastics offer next to the recycling aspects, option for new structural designs, manufacturing and bonding concepts (basic and applied research, pilot actions, demonstration actions).
- Development of biopolymers to replace the organic mineral oil based resins. These resins made from biological products also link to a vision for the longer future (basic and applied research, pilot actions).
- Development of blades suited to incorporate the distributed control devices without decreasing the reliability and without increasing the required maintenance (basic and applied research, pilot actions, demonstration actions).

Recommended research activities (*basic and applied research, pilot actions*)

To address the short term challenges, EU stimulated research projects offer a excellent possibility to coordinate and stimulate the research activities amongst the major European R&D organisations and industries in this field. A good cooperation between these organisations has been achieved in the recent past and very good results have been achieved so far. But a continuation of this type of R&D is required

to meet the short term challenges and to complete the understanding of the fibre reinforced materials behaviour and damage monitoring.

To address the long term challenges research needs to be stimulated with respect to new material development and recyclability (*basic and applied research*). To address the development of a cost efficient and very light weight new blade concept design studies and the demonstration of revolutionary designs need to be stimulated (*pilot and demonstration actions*). This research could be implemented into the development and manufacturing of a concept blade like “race car” were irrespective of cost optimisation all new features can be developed and demonstrated. In this project a precompetitive collaboration is required between industries and R&D organisations. After the different blade features have been demonstrated the industries can develop their own concept blades with the demonstrated features.

This approach can be applied for different components in the wind turbine and even for a complete revolutionary wind turbine.

6.1.2 Tower and support structure

For market implementation, the critical aspect will be the recognition of the material and assembly by certification authorities. Each wind turbine needs to be certified according to accepted design rules, that are published in public (for example Eurocode) or private (for example DNV or Germanische Lloyd recommended practices) documents.

Integral design approaches in which the wind industry collaborates with the steel industry and fabricators are a prerequisite for the development of light weight steel components and structures for wind turbines. Development and utilization of new materials is only possible if material specifications are developed between the specifying wind turbine industry and the supplying steel industry, while current practice is to refer to standard grades, which inhibits new developments. Considering the geographical dispersion of the actors (wind turbine designer, fabricator, steel producer), funding at the European level is welcome because national funding will generally be able to support a part of the supply chain.

To address these challenges the following R&D activities are required (*basic and applied research, pilot and demonstration actions*):

Materials:

- Development of high strength steels, heavy gauge (thickness above 30mm), with superior toughness (-50°C) suited for welding technology such that the welded joints sustain loads of above 90 or 100MPa at 4×10^6 cycles. Superior toughness should be provided also for welding techniques with very high heat input.
- Development of specialized pre-stressed concrete.
- Development of light-weight composite towers.

Welding processes to be developed and implemented:

- Welding techniques with high efficiency in terms of productivity (automatic or robotised submerged arc welding [59-65], low heat input combined with reduced consumable consumption (laser welding [66-79], [87,88], non-vacuum electron beam shop floor welding: GMA welding, hybrid- friction stir welding [80-86].

Erection (assembling joints) to be developed and implemented:

- Field welding: automatic or robotised GMA welding procedures, bolt connections: flange connections, friction connections [89]

One of the options for future support structures is the further development of gravity based concrete support structures for deep water application and the development of drilled concrete monopiles for applications up to 40 to 50 m [97, 98]. Concrete is more maintenance friendly and faces less corrosion issues than steel. Until now gravity based support structures have been mostly used in shallow waters. But since the application of steel monopiles and jacket structures requires hammering activities, which limits

the installation window due to environmental considerations and also from economical viewpoint concrete (gravity based) support structures offer good perspectives for applications also in deeper water.

Applied research is required on the development and application of the concrete gravity based and drilled concrete monopole support structures for deep water applications.

At a somewhat later stage *pilot and demonstration actions*, requiring large budgets, will be needed to convince industry and certifying bodies.

6.1.3 Transmission

Reduction of maintenance, reduction of weight, increase of efficiency, performance improvement by alternative designs and integrated solutions will be the technological driving force for transmission components. In order to avoid bottlenecks, knowledge diffusion and transfer is needed. The new designs will rely heavily on different competencies such as metallurgy, surface treatment, tribology, lubrication, mechanical and surface fatigue, which need to be supported by integrated R&D projects. The R&D effort is to be carried out at European level considering the throughout Europe presence of wind transmission companies. The national level may prevent the European integration. The size of EU projects should be maintained in the range 2-5 M€ for research projects and even much larger for demonstration projects.

Specific issues to be addressed in the research are (*basic and applied including pilot and demonstration activities*):

Material alloy, heat treatment, and surface treatment selection strategies:

- Measure the bearing behaviour and damage under varying conditions of load magnitude, load transients and slip.
- Bearing rating standard: modify DIN ISO 281 to include the influence of micro-damages on calculated bearing life.
- Steel production with lower non-metallic inclusions.
- Better detection technology of exogenous inclusions on gear blanks.
- Technologies to produce large gears cost efficiently.
- Foundry technology for dross-free ductile iron with higher strength and very high wall thickness.
- Gearbox lubricants: development of new durable, stable, non-corrosive, environmentally friendly and available lubricants.
- Solid contaminant influence and revision of established oil cleanliness requirements for wind turbine gearboxes.
- Durable (non-metallic) components, paints and sealants, complying with environmental legislation.
- Development of light-weight composite and hybrid materials for gearbox housings.

Manufacturing aspects:

- Determine the influence that various grinding and finishing techniques have on surface topography of gear teeth and rolling element bearing surfaces and establish the degree (cost) of surface finishing required to reduce the incidence of micro-damages in materials that vary in composition, hardness, and heat treatment.
- New surface treatments such as PVD coatings, nitriding treatments and laser treatment to improve gear teeth properties.
- Develop durable processes, complying with environmental legislation (insulation materials, flue gasses and waste water, lubricants and cleaning agents).

Damage testing and condition monitoring:

- Test rigs for collective test methods of gear units in overload.
- Same for cold climate applications.

- Scaling up of FZG² test procedures for new technology implementation, such as sets of material and surface treatment.

Allow standardization of laboratory-scale tests to be used to cost-effectively and accurately screen lubricants, surface treatments, and coatings.

6.1.4 Nacelle bedplate and rotor hub

Research to improve foundry technology to support wind turbine manufacturing current foundry technology is struggling to support the increasing sizes of items and quantity. Therefore the following R&D activities are required (*basic and applied research, pilot and demonstration actions*):

- Improved geometry through improved foundry technology, (weight/cost reduction to be reached) (Up to 25% reduction in weight if the design gives the geometry and not the casting process),
- Better control of metallurgy and mechanical properties through improved controlled casting (gating systems, flow of melt, mould material) this will allow a uniform internal structure or even better a designed internal microstructure dependant on loads under operation,
- Allow for improved reliability and durability of wind turbine components by increased knowledge in manufacturing process and the possibility of tailor making the material properties to the use.
- Development of light-weight composite structures for rotor hub and bedplate

6.1.5 Electricity generator and power converter

The European wind industry claims the EU has to change its approach from supporting European renewable energies to supporting the European renewable energy industry [101], and these claims should be attended. The *basic and applied research* on both higher-efficiency use, and substitution, of REEs in permanent magnets presents high risk and has a European scope. The umbrella of these mechanisms should allow European firms and research centres to share and optimise the cost of this research.

After the experience of the trans-European networks facilitators, one such mechanism could be the establishment of a European facilitator -and an Office of the European facilitator- for *basic and applied research* on permanent magnet technology. With an orientation at materials level and aiming at enabling the coordination of European research by sharing the information (e.g. on who does what), tackling intellectual property rights and other issues that currently hinder the more efficient use of European R&D funds.

Government funding of *pre-competitive research* on enabling material alternatives combined with international coordination; early (financial) involvement of industry to steer and apply material research [102]. The practical objectives should be reducing REE content in PM, use of alternative materials for PM manufacture, and design for recycling.

Basic and applied research and pilot and demonstration activities for high temperature superconductors (HTS) research should tackle the price of coated conductors, which must be reduced by an order of magnitude by 2030.

Direct-current (DC) electricity transmission, a necessary prerequisite for DC generators in a DC-based wind farm, has as research needs a better understanding (and an optimisation) of the long-term ageing of DC insulation as well as a better understanding of the breakdown mechanism on DC [113]

Power electronics devices could be subject to industry-led joint basic research aimed at increasing the working and limit junction temperatures, which would enable higher energy/power intensity.

6.1.6 General

The kind of research needed to obtain breakthroughs is plagued with risks. However, most research programmes are adverse to risks – but no risks = no breakthroughs. Some programmes, in particular in basic science, should be re-designed to allow for higher risks.

² FZG stands for "Forschungsstelle für Zahnrad und Getriebebau", the German Technical Institute for the Study of Gears and Drive Mechanisms.

Discussions during the last UpWind meeting (15-18 February 2011) with representatives from industry led to the advice to establish next to the basic and applied research and demonstration projects to (virtual) R&D centres in the different wind turbine materials development areas.

Especially in the field of:

- Development blade composite materials and related manufacturing techniques
- Gearbox research and related manufacturing techniques
- Development of high strength casting and forging materials and related production techniques
- Development high strength materials and related designs for tower and support structure.

6.2 Needs and recommendations for market implementation in 2050

The political approach of 20-20-20 will be reflected mainly throughout Europe for the next decade. In 2030, wind energy will be a major global energy source. Markets will be driven by concerns over the impacts of: climate change; oil and gas depletion; the high cost and unpredictable availability of fuel (security of supply); and CO₂ allowance prices and sustainability.

Considering offshore and harsh conditions wind potential exploitation the evidenced bottlenecks for wind energy sector can be overcome through additional long term material R&D, i.e. through the application of targeted funding and other resources. To ensure, next to that, the European technology leadership on the very long term, the development of very large (offshore) wind turbines, up to 20 MW has to be stimulated through basic research and applied research projects.

Specific EU research dimensions cooperative instruments of an average dimension among 2 and 5 M€ funding dedicated to the topics described below, can strongly help the cooperation.

6.2.1 Blades

To address the challenges on the long term the following activities are recommended (*basic and applied research*):

- Development of new design and production technologies to drastically reduce the weight of the blade while maintaining all the functional and life time requirements.
- Development of ‘smart blades’ concepts for the very large blades for offshore wind turbines. The control devices and sensors of these blades must require very low maintenance and have to withstand lightning strikes
- Development of recycling and reuse strategies for the worn out blades, including the application of natural fibres in thermoplastic resins or in biopolymers.

6.2.2 Nacelle bedplate and rotor hub

Research in higher quality materials for structural parts in nacelles and hub in order to support size of future Wind turbine components (*basic and applied research*):

- Allow WTG designers a range of alternative light weight construction materials that allow for stronger and more slender design, key criteria being.
- Price competitiveness, low temperature properties, high fatigue properties, high yield strength, elongation and stiffness

6.2.3 Transmission

The topics to be deeply explored to address the long term materials’ challenges are (*basic and applied research*):

- Set-up of test methods, to evaluate material (alloy, heat and surface treatment, nitriding, laser heat treatment, laser remelting, laser alloying and laser ablation, PVD coatings)

- selection rules to help designers avoid micro-damages (micropitting, abrasion, macropitting, scuffing) with improved lubrication
- Determine the influence of surface topography and improved damage sensors to identify condition monitoring strategies that can sensitively detect the early presence of damages in operating components.
- Biodegradable lubricants.

7. Acknowledgements

The report has been discussed in a stakeholders meeting organized by de Commission on the 4th of April of 2011 which included the presence of Albert Kriener (E.ON); Jan Schamp (Hansen Transmissions); Pep Prats (Alstom Power-TPWind); Jos Beurskens (Energy research Centre of the Netherlands-TPWind); Athanasia Arapogianni and Filippo Gagliardi (EWEA-TPWind); Jaap de Boer (Suzlon); Bertrand de Lamberterie (Steel Research, ESTEP); John F. Hill (Converteam); Jose Maria Albuquerque (ISQ-EUMAT) and Amaia Igartua (TEKNIKER-EUMAT); Brian Norton (Indestructible Paint-BCF) Martijn Geertzen (NEN-CENELEC); Larissa Gorbatikh (K. U. Leuven); and George Kariniotakis (MINES ParisTech). The comments made in this meeting and the subsequent exchanged were used to update this report.

In addition to the former, we would like to acknowledge the very valuable contribution from the following persons: Alain Guy (Converteam), H. Polinder (T. U. Delft), J. F. Reyes (Atlas Magnetic Group), J van Rossum (Dredging International), F. Nuño (European Copper Institute), N. Athanassopoulou (Cambridge University), L. Vandebbossche (Arcelormittal).

8. References

- 1 Global Wind Energy Council: Global Wind statistics 2010
- 2 Llorente Iglesias, R; Lacal Arantegui, R; Aguado Alonso, M: *Power electronics evolution in wind turbines – a market-based analysis*. Renewable and Sustainable Energy Reviews 15 (2011) 4982– 4993, doi:10.1016/j.rser.2011.07.056
- 3 DoE (U.S. Department of Energy): *Critical Materials Strategy*. December 2010
- 4 Brøndsted, P.; Lilholt, H.; Lystrup, Aa., *Composite materials for wind power turbine blades*. Ann. Rev. Mater. Res. (2005) 35 , 505-538
- 5 Brøndsted, P., Holmes, J.W., Sørensen, B.F. *Wind Rotor Blade Materials Technology*. European Sustainable Energy Review (2008) (no.2) , 36-41. 2008
- 6 Hayman, B.; Wedel-Heinen, J.; Brøndsted, P.: *Materials challenges in present and future wind energy*. MRS Bulletin (2008) 33 , 343-353. 2008
- 7 N.Papadakis, C.Ramírez, N.Reynolds. *Designing Composites Wind Turbine Blades for Disposal, Recycling or Reuse*. In: Management, Recycling and Reuse Of Waste Composites. Ed. Vanessa Goodship. Woodhead Publishing in materials. 2010. ISBN 978-1-84569-462-3
- 8 *Global gaps in clean energy R&D*. Update and Recommendations for International Collaboration. IEA Report for the Clean Energy Ministerial. 2010.
- 9 Fichaux, N.: *Delivering today the energy of tomorrow*. EWI – The European Wind Initiative European Wind Energy Technology Platform. July 2009.
http://www.windplatform.eu/fileadmin/ewetp_docs/Events/European_Wind_Initiative_-_JP.pdf

- 10 ENERGY 2010. Annual report 2010 on public grants from energy research programmes ForskEL, EDDP/ERP, ELforsk, DSCR Energy and Environment and energy projects of the Danish National Advanced Technology Foundation. 2010.
- 11 J. Beurskens: *Developing Offshore Wind Energy now and in the future*. Third We@Sea Conference, IJmuiden, November 25, 2010. <http://www.we-at-sea.org/leden/docs/conference2010/1.pdf>.
- 12 TPWind: *The Way Forward*. March 2009. 6 Frame Work Programme.
- 13 *Profile of the Danish Wind Industry*. Denmark wind power hub. Danish Wind Industry Association. Ministry of Foreign Affairs. 2011. <http://www.e-pages.dk/windpower/21/>
- 14 RenewableUK (BWEA). *UK Offshore Wind: Staying on Track. Forecasting offshore wind build for the next five years*. <http://www.bwea.com/pdf/publications/CapReport.pdf>
- 15 *Doing Business with Wind Turbine Manufacturers*. DTI Scottish Enterprise. A report to DTI and Scottish Enterprise by Douglas-Westwood Limited and BVG Associates, July 2006. <http://www.bvgassociates.co.uk/LinkClick.aspx?fileticket=YcePAzeHDQc%3D&tabid=101>
- 16 *American wind power surmounted challenges in 2010*. http://www.awea.org/rn_release_01-06-11.cfm
- 17 *AWEA Third Quarter 2010 Market Report*. October 2010. http://www.awea.org/documents/reports/2010_third_quarter_report.pdf
- 18 *Winds of Change. A Manufacturing Blueprint for the Wind Industry*. AWEA. June 2010. http://www.awea.org/la_pubs_reports.cfm.
- 19 *WindVision 2025. A strategy for Quebec*. Canadian Wind Energy Association. 2010.
- 20 VESTAS. *V 112 3.0 MW Offshore*. www.vestas.com.
- 21 ENERCON *Wind energy converters*. Products overview. www.enercon.de.
- 22 GAMESA. *G128-4,5 MW*. www.gamesacorp.com.
- 23 SIEMENS Wind Turbine. *New dimensions.SWT-3.6-107*: www.siemenswindpower.com.
- 24 Repower system. *The 5-megawatt power plant with 126 meter rotor diameter*. Technical data. pdf. www.repower.com.
- 25 GE Power & Water. *Renewable Energy. 4.0-110 Offshore Wind Turbine*. www.gewindenergy.com.
- 26 D. Acona, J. Mc Veigh: *Wind Turbine – Materials and Manufacturing Fact Sheet*. US Department of Energy. C-1 – C-8. 2001.
- 27 Aldeman. M.: *Building the Wind Turbine Supply Chain: The Next Steps Workshop*. Illinois WindWorking Group. Illinois State University. July 2010. <http://renewableenergy.illinoisstate.edu/wind/conferences/speaker%20presentations/071310%20IWWG%20Supply%20Chain%20Workshop/SC%20071310%20AM%201045%20Matt%20Aldeman%20Opportunities.pdf>
- 28 European Wind Energy Association, September 2009, *Oceans of Opportunity, Harnessing Europe's largest domestic energy resource*,.
- 29 <http://www.vattenfall.co.uk/en/ormonde.htm>
- 30 Robinson, J.G., et al. Fabrications Ltd. *Presentation to UK Offshore Wind Supply Chain Event*, 4 February 2010
- 31 DNV Offshore Standard DNV-OS-J101 *Design of Offshore Wind Turbine Structures*, October 2007, amended Nov 2009.
- 32 BNEF (Bloomberg New Energy Finance): *Wind Energy Research Note: Driving to 5 MW and beyond*, 2nd June 2010.

- 33 E. Martínez, F. Sanz, S. Pellegrini, E. Jiménez, J. Blanco: *Life cycle assessment of a multi-megawatt wind turbine*. Renewable Energy 34 (2009) 667-673.
- 34 John F. Hill: *Wind Turbines – the Era of the Permanent Magnet Generator*. Presented at the seminar on “Permanent Magnets – The Rare Earth Crisis” of the UK Magnetics Society, 2nd December 2010.
- 35 John F. Hill, Marketing Manager, Converteam Renewables. Email communications, 7th and 24th February, and 6th April 2011.
- 36 PowerGen World Wide: *Superconducting generator: one small step?* 1st February 2011, accessed on 15.02.11 at <http://www.powergenworldwide.com/index/display/articledisplay/8435051715/articles/power-engineering-international/volume-18/issue-2/features/superconducting-generator.html>
- 37 EWEA: *Powering Europe: wind energy and the electricity grid*. November 2010
- 38 International Energy Agency: *Energy Technology Perspectives 2008, Scenarios and Strategies to 2050*, 2008.
- 39 BTM Consult AsP, *World Market Update 2010*
- 40 L.D. Willey. *Design and Development of Megawatt Wind Turbines*. In Wind Power and Wind Turbine Design. Ed. Wei Tong. WIT Press 2010. ISBN 978-1-84564-205-1
- 41 Denja Lekou; *Scaling limits & costs regarding WT blades*. UpWind report, September 2010
- 42 N.Reynolds and M. Pharaoh. *An Introduction to Composites Recycling*. In: Management, recycling and reuse of waste composites. Ed. Vanessa Goodship. Woodhead Publishing in materials. 2010. ISBN 978-1-84569-462-3
- 43 E. Witten. *The Composites Market in Europe: Market Developments, Challenges, and Opportunities*. AVK - Industrievereinigung Verstärkte Kunststoffe (Federation of Reinforced Plastics). 2008. <http://www.eucia.org/uploads/cf91cb671a72c3a9c26b2e91c6edab57.pdf>
- 44 Global Glass Fiber Industry: *Global Glass Fiber Market 2010-2015, Trends Forecasts and Opportunity Analysis*; http://www.researchandmarkets.com/reportinfo.asp?report_id=1196476&t=d&cat_id=
- 45 <http://www.newenergyworldnetwork.com/renewable-energy-news/by-technology/wind/>
- 46 UpWind project: <http://www.upwind.eu>
- 47 John F. Mandell, Herbert J. Sutherland: *Effects of Materials Parameters and Design Details on the Fatigue of Composite Materials for Wind Turbine Blades*. EWEC conference 1999.
- 48 L.G.J. Janssen and others. *Reliable optimal use of materials for wind turbine rotor blades (OPTIMAT BLADES)*, Final report, EC project no. NNE5-2001-00174 (2006)
- 49 Optidat material date base: http://www.wmc.eu/optimatblades_optidat.php
- 50 Jakob Wedel-Heinen: *Implementation of OPTIMAT in Technical Standards OB_TG6_R002 rev. 8*: www.wmc.eu/public_docs/10317_008.pdf
- 51 Blade King Project: www.netcomposites.com/newsitem.asp?id=4986
- 52 E. Stammes and others: *Subcomponent testing for wind turbine blades*; UpWind website. 2010
- 53 F. Sayer: *Subcomponent testing for wind turbine blades*. www.dewek.de/fileadmin/pdf/abstracts/S18_3.pdf
- 54 Andreas Makris & Carla Ramault: *Biaxial fatigue testing of cruciform composite specimens*; 2010 UpWind website
- 55 INNWIND; <http://www.innwind.nl>
- 56 Mandell, J.F., Samborsky, D.D., Agastra, P., Sears, A.T., and Wilson, T.J., "*Analysis of SNL/MSU/DOE Fatigue Database Trends for Wind Turbine Blade Materials*," Contractor Report SAND2010-7052, Sandia National Laboratories, Albuquerque, NM (2010).

- 57 T K Barlas and G A M van Kuik; *State of the art and perspectives of smart rotor control for wind turbines*; Journal of Physics: Conference Series, Volume 75, 2007
- 58 Kjeld van Rijswijk and Harald Bersee: *Thermoplastic Composite Wind Turbine Blades*
- 59 R. Paschold, D. Dirksen: *Submerged arc welding of steels for offshore wind towers*. Svetsaren. Vol. 60, no 1, pp. 13-17, 2005.
- 60 B. Torstensson, P. Ivarson: *ESAB welding solutions for windmill tower production. Processes and equipment for increased productivity*. Svetsaren. Vol. 60, no 2, pp. 14-19, 2005.
- 61 *Efficient welding in the wind tower manufacturing industry*. ESAB. Brochure XA00126920.
- 62 Eric de Man, W. Lafleur: *SIF Group bv at the foundation of Dutch wind energy*. Svetsaren. Vol. 63, no 1, pp.18-22, 2008.
- 63 M. Sharpe: *Robotic fabrication of wind turbine power generators*. Welding Journal. Vol. 88, no. 8, pp. 40-44, 2009.
- 64 *Wind Turbine Welding System Uses Linear Motion Modules*. Welding Journal. Vol. 88, no. 8, pp. 50-51, 2009.
- 65 *Wind Energy. An Oerlikon Market Solution*. Brochure. AIR LIQUIDE. WELDING.
- 66 C.Thomy, G. Sepold, T. Seefeld, C. Walz, R. Hoffmann, I. Stiebe-Springer, M. Koçak, R. Segar: *Industrial Implementation of Laser/GMA Welding and Mechanical Properties of the Welds*. In: Proc. Supermartensitic Stainless Steels 2002 Conference. Brüssel, KCI Publishing BV, Zutphen, pp.147-155, 2002.
- 67 G.Sepold, C. Thomy, T. Seefeld, M. Schilf, F. Vollertsen, R. Hoffmann: *CO2-Laser GMA Hybrid Welding - Aspects of Research and Industrial Application*. In: Proc. Lasers in Manufacturing 2003, AT-Fachverlag, Stuttgart, pp.149-156, 2003.
- 68 H. Staufer: *Laser hybrid welding of ships*. Welding Journal, Vol. 83 no. 3 pp.39-43. 2004.
- 69 C.Thomy, T. Seefeld, F. Vollertsen: *Application of High-Power Fibre lasers in Laser and Laser-MIG Welding of Steel and Aluminium*. In: Proc. IIW Annual Assembly Conference, July 10th - July 16th, Prague, Czech Republik, pp. 88-98. 2005.
- 70 H. Staufer, T. Graf: *Laser hybrid welding drives VW improvements*. Welding Journal, vol. 82, no. 1, pp.42-48, 2003.
- 71 Proceedings of the 2004 Advanced Laser Applications Conference & Exposition. Michigan USA, SEPTEMBER 20-22, 2004. Reutzel E.w> et al.: *Joining Pipe with Hybrid Laser-GMAW Process: Weld Test Results and cost Analysis*. Welding Journal. 2006. vol. 85. no 6, pp.66-71.
- 72 H. Staufer: *Laser Hybrid Welding and Laser Brazing at Audi and VW*. Welding in the World, vol. 50, no 7/8, 2006.
- 73 H. Ozden: *Investigating fiber lasers for shipbuilding and marine construction*. Welding Journal. 2007. Vol. 86. No. 5, pp.26-29.
- 74 H. Staufer: *Laser hybrid welding in the automotive industry*. Welding Journal. 2007. Vol. 86. No 10, pp.36-40.
- 75 J. Defalco: *Practical applications for hybrid laser welding*. Welding Journal. 2007. Vol. 86. No. 10, pp.47-51.
- 76 L-E. Stridh: *Welding of 13% Cr-steels using the laser-hybrid process*. Svetsaren, 2007, vol. 62, no. 1, pp.34-36.
- 77 F. Ohlsen: *Hybrid laser arc welding*. Woodhead Publishing, Camebridge (2009).
- 78 C. Li, K. Muneharua, S. Takao, H. Kouji: *Fiber laser-GMA hybrid welding of commercially pure titanium*. Materials and Design, 30 (2009), pp.109-114.

- 79 S.M. Kelly et al.: *Using Hybrid laser Arc Welding to reduce Distortion in Ship Panels*. Welding Journal. 2009. vol. 88. no 3, pp.32-36.
- 80 T. J. Linert et al.: *Friction stir welding studies on mild steel*. Welding Journal, Vol. 82, no 1, pp. 1- -9-s, 2003.
- 81 Ozekcin, et al.: *A Microstructural Study of Friction Stir Welded Joints of Carbon Steels*. International Journal of Offshore and Polar Engineering. Vol. 14, No. 4, pp.284-288, December 2004.
- 82 M. Norris, W. M. Thomas, J. Martin, D. J. Staines: *Friction stir welding - process variants and recent industrial developments*. 10th International Aachen Welding Conference, 'Welding and Joining, Key Technologies for the Future', Eurogress, Aachen, 24-25 Oct. 2007.
- 83 J. Defalco, R. Steel: *Friction Stir Process Now Welds Steel Pipe*. Welding Journal. Vol. 88, no 5, pp.44-48. 2009.
- 84 Santos, T. F. A., *Friction stir welding of UNS S32205 duplex stainless steel*. LNLS 2009 Activity Report.
- 85 T. Saeid, et al.: *EBSD Investigation of Friction Stir Welded Duplex Stainless Steel*. World Academy of Science, Engineering and Technology. Vol. 61, pp.376-379, 2010.
- 86 Z. Feng, et al.: *Friction Stir Spot Welding of Advanced High-Strength Steels –A Feasibility Study*. Report no 2005-01-1248. 2005 SAE International.
- 87 RFSR-CT-2005-00042: *Fatigue Behavior of High Strength Steels Welded Joints in Offshore and Marine Systems – FATHOMS*. Final Report. Coordinator: CSM, Sp. Italy. 2009.
- 88 RFSR-CT-2006-00029. *Improvement in Steel Utilization and Manufacturing by Recent Break-through in High-power Fibre Laser Welding*. Final Report. Coordinator: BIAS, Germany Bremer Institut für angewandte Strahltechnik GmbH, "BIAS". 2009.
- 89 RFSR-CT-2006-00031: *High-Strength Steel Tower for Wind Turbine*. Final Report. Coordinator: Lulea University of Technology, Sweden. 2010.
- 90 FP7 – 212825 *Procedures for testing and measuring wind energy systems (PROTEST)* End date: 2010-08-31
- 91 FP7 – 212966 *Reliability focused research on optimizing wind energy systems design, operation and maintenance: tools, proof of concepts, guidelines & methodologies for a new generation (RELIWIND)* End date: 2011-03-14
- 92 FP6 – 30433 *Development of gear drive trains based on new materials and novel gear systems (X-GEAR)* End date: 2009-08-31
- 93 Spomenka Kobe, Jozef Stefan Institut, Slovenia. Presentation on *Rare Earth Magnets in Europe* at the Trans-Atlantic Workshop on Rare Earth Elements and Other Critical Materials for a Clean Energy Future. 3rd December 2010.
- 94 Mishnaevsky, Leon; Brøndsted, Povl. *Micromechanical modelling of damage and fracture of unidirectional fiber reinforced composites : A review*. In: Computational Materials Science, vol: 44(4), p. 1351-1359 (2009). Elsevier Science BV 2009
- 95 Erich Hau, *Wind turbine Fundamentals*, 2nd edition pagg 294 and 393
- 96 Hywind:
<http://www.statoil.com/en/TechnologyInnovation/NewEnergy/RenewablePowerProduction/Offshore/Hywind/Pages/HywindPuttingWindPowerToTheTest.aspx>
- 97 E. van de Brug; *Drilled concrete monopile*. http://www.offshore-energy.nl/content/files/SITE4512/executive_summery_monopile.pdf
- 98 K. Weber; *The base of Power*, German Norwegian Offshore Energy Conference.2010;
http://www.windenergie-agentur.de/deutsch/aktuelles/WAB-Veranstaltungen/Studienreise-Norwegen/PDF/19_Strabag_Weber.pdf

- 99 Lynas Corporation Ltd. 2014 estimates of rare earths supply and demand.
- 100 Database of wind turbine models and installations created by the JRC
- 101 European Commission *Supporting & Monitoring techno-economic analyses in the field of alternative energy technologies*. Enerdata/ECN for the Joint Research Centre, European Commission, Brussels 2011.
- 102 Materials innovation institute. Presentation of the *Materials scarcity report and industrial perspectives* at the Trans-Atlantic Forum, Boston (US) 3rd December 2010.
- 103 American Physical Society panel on public affairs/Materials Research Society, US: Energy Critical Elements: Securing Materials for Emerging Technologies. February 2011. Available at <http://www.aps.org/policy/reports/popa-reports/loader.cfm?csModule=security/getfile&PageID=236337>
- 104 IMCOA, cited by T. Lograsso from The Ames Laboratory, US DoE, in his presentation at the Trans-Atlantic Forum, Boston (US) 3rd December 2010.
- 105 Los Alamos National Laboratory: Ultraconductus, 2010 R&D 100 Awards Entry Summaries, consulted on 25/02/11 at http://www.lanl.gov/source/orgs/tt/awards/rd100/summaries/10_execsum.shtml.
- 106 Siemens' wind power technical solutions available on-line at <http://www.automation.siemens.com/mcms/large-drives/en/ld/solutions-industry/windpower/Pages/windpower.aspx>, consulted 25/02/11.
- 107 Adamczyk A., Teodorescu R., Mukerjee R.N., Rodriguez P. 2010. *FACTS devices for large wind power plants*. Paper presented at the 3rd EPE (European Power Electronics and Drives Association) Wind Energy Chapter Seminar in Stafford on the 15th and 16th of April 2010.
- 108 P. Tixador: *Development of superconducting power devices in Europe*. Physica C 470 (2010) 971–979
- 109 Convertean press release 6th December 2010: “*Converteam and Scottish and Southern Energy join forces on Offshore Wind Energy*” to demonstrate a DC generator that can be integrated in a DC array and connected to the shore through a HVDC cable.
- 110 Chen Z., Guerrero J.M., Blaabjerg F. (2009b). *A review of the state of the art of power electronics for wind turbines*. IEEE Transactions on power electronics, vol. 24, No 8, August 2009.
- 111 Testimony of Mark A. Smith, CEO, Molycorp Minerals LLC, to the Subcommittee on Investigation and Oversight, House of Science and Technology Committee, US Congress 16.03.10.
- 112 ADEPT (2010): *Agile Delivery of Electrical Power Technology, a research programme part of the US DoE ARPA-E programme*. Consulted 10th October 2010 at <http://arpa-e.energy.gov/ProgramsProjects/ADEPT.aspx>
- 113 Interviews of JRC staff to industry representatives at the Husum 2010 wind energy fair. These include Vensys, E.ON, SEwind, The Switch, and many others.
- 114 Lynas Corp, information extracted from annual reports 2001-2010 and their web site http://www.lynascorp.com/page.asp?category_id=1&page_id=25 consulted 12th December 2011.
- 115 http://cordis.europa.eu/fetch?CALLER=FP7_PROJ_EN&ACTION=D&DOC=8&CAT=PROJ&QUERY=012f41c77064:b7a0:581aea0a&RCN=88798
- 116 Koziol K, Vilatela J, Moisala A, Motta M, Cunniff P, Sennett M, Windle A. *High-Performance Carbon Nanotube Fiber*. Science 2007;318:1892.
- 117 Böger L, Sumfleth J, Hedemann H, Schulte K. *Improvement of fatigue life by incorporation of nanoparticles in glass fibre reinforced epoxy*. Composites Part A: Applied Science and Manufacturing;41:1419.
- 118 http://www1.eere.energy.gov/office_eere/pdfs/wind_tower_systems_sbir_case_study_2010.pdf
- 119 <http://www.reinforcedplastics.com/view/8460/ashland-to-supply-resin-for-wind-turbine-tower-project/>

- 120 <http://engineering.umaine.edu/blog/2010/08/04/off-shore-wind-blades-yes-towers-maybe/>
- 121 <http://www.nwip.org/casestudies/cmt.html>
- 122 J. F. Reyes, Atlas Magnetics Europe B.V., personal conversation.
- 123 *Lifecycle Assessment of a V90-3.0 MW offshore wind turbine*. Vestas Wind Systems A/S
- 124 Frost & Sullivan: *copper content assessment of wind turbines, de-brief meeting*. Presented to the European Copper Institute, 12th July 2010
- 125 Öko-Institut (2011), *Study on Rare Earths and Their Recycling*.
- 126 Hatch, G. P.: *Critical Rare Earths - Global supply & demand projections and the leading contenders for new sources of supply*. Technology Metals Research, August 2011.
- 127 Avalon Rare Metals Inc., corporate presentation 24th November 2011, available at http://avalonraremetals.com/resources/presentation/Corporate_Presentation_2011_11_30.pdf
- 128 Blog Technology Metals Research, consulted at different moments. Available at <http://www.techmetalsresearch.com/>
- 129 Lynas Corp: press release 15th July 2011: Chinese Rare Earths Export Quota Released for Second Half 2011. Available on line at <http://www.asx.com.au/asxpdf/20110715/pdf/41zshtqzvqgbdx9.pdf>, consulted 3rd January 2012.

European Commission

EUR 25197 EN – Joint Research Centre – Institute for Energy and Transport

Title: Scientific Assessment in support of the Materials Roadmap enabling Low Carbon Energy Technologies. Wind Energy

Author(s): L.G.J. Janssen (rapporteur), R. Lacal Arántegui, P. Brøndsted, P. Gimondo, A. Klimpel, B.B. Johansen, P. Thibaux

Luxembourg: Publications Office of the European Union

2012 – 45 pp. – 21 x 29.7 cm

EUR – Scientific and Technical Research series – ISSN 1831-9424 (online), ISSN 1018-5593 (print)

ISBN 978-92-79-22936-7 (pdf)

ISBN 978-92-79-22935-0 (print)

doi:10.2790/42568

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Abstract

The European Strategic Energy Technology Plan (SET-Plan), adopted by the European Union in 2008, is a first step to establish an energy technology policy for Europe. The SET-Plan will support the 2020 energy and climate change objectives through the establishment of the European Industrial Initiatives (EII) for low-carbon energy technologies.

One of the SET-Plan initiatives to support the EII is to analyse the materials that will be needed in order to achieve the 2020 targets, in terms both of amounts and of technical specifications, and the way to get there. For this, the SET-Plan Materials initiative was created to foster a roadmap which is based on the corresponding scientific assessment. This assessment, whose wind energy aspects are presented in this report, includes the aspects of technology and system state-of-the-art and challenges; material supply status and challenges; ongoing research and actors, and challenges; materials specification targets for market implementation in 2020/2030 and in 2050; synergies with other technologies; and needs and recommendation of activities addressing 2020 and 2050 market implementation.

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